Analysis of Link-Node Model Mass Loading Scenarios

Report 4.8.5

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List of Acronyms

R_{Flow}	equivalent oxygen demand resulting from decreased net flow due to upstream diversions
BOD	biochemical oxgyen demand
c	observed DO concentration
$\bar{c}$	mean observed DO concentration
CDEC	California Data Exchange Center
cfs	cubic feet per second
CVRWQCB	Central Valley Regional Water Quality Control Board
DO	dissolved oxygen
DO_{meas}	measured DO concentration
DO_{obj}	DO criterion of 6 mg L^{-1} in the months of September through November and 5 mg L^{-1} during all other months
DWR	Department of Water Resources
DWSC	deep water shipping channel
EERP	Ecological Engineering Research Program
ENOD	excess net oxygen demand
kg	kilograms
L	liter
$\sum LA$	sum of load allocations resulting from non-point source pollution
lb	pounds
mg	miligrams
MOS	margin of safety
n	number of data points
NH_4^+-N	total ammonia nitrogen
NPDES	National Pollution Discharge Elimination System
QA/QC	quality assurance/quality control
Q_{DWSC}	25 hour average net flow rate
R^2	coefficient of determination
R_{DWSC}	equivalent oxygen demand resulting from changes in channel geometry
RRI	Rough and Ready Island
RWCF	regional wastewater control facility
SJR	San Joaquin river
TMDL	total maximum daily load
WARMF	Watershed Analysis Risk Mangement Framework
$\sum WLA$	sum of waste load allocations resulting from point source pollution
x	model DO concentration

Introduction

In this report, we present the results of Link-Node Model simulations that were performed to determine the conditions and sources of oxygen-consuming substances and nutrients that contribute to low dissolved oxygen (DO) conditions in the Stockton Deep Water Ship Channel (DWSC), located in the lower reaches of the San Joaquin River (SJR). This study was conducted by the Ecological Engineering Research Program (EERP) at the University of the Pacific and Systech Engineering as a part of the SJR DO Total Maximum Daily Load (TMDL) Project (E0883006). The purpose of the project and of the work described herein was to identify sources of pollution in order to develop strategies to mitigate low DO conditions in the SJR estuary. This work addresses Subtasks 4.7 and 4.8 of the project.

The Link-Node Model, developed as part of the previous DO TMDL studies, simulates the tidally influenced lower SJR between the junction with Old River near Mossdale and Light 18 located within the DWSC (Herr et al., 2008). It was designed to work in conjunction with the Watershed Analysis Risk Management Framework (WARMF) model, which simulates rainfall, runoff, and discharge in the highly agricultural upper SJR watershed from Friant Dam to Old River (Herr, et al., 2008). As part of this study, the Link-Node Model was improved and recalibrated by Systech Engineering in November 2012 using observed DO data recorded at the Rough & Ready Island (RRI) flow and water quality monitoring station. In May 2013, the Link-Node Model was again calibrated using the same DO data set, but with improved wind data, improved BOD decay rates, and an improved re-aeration adjustment factor (Appendix 5.1.1, Sheeder and Herr 2013). Available DO and flow data were collected from the California Data Exchange Center (CDEC) to evaluate the accuracy and precision of two calibrated Link-Node Models. Mean relative error and mean absolute error, calculated using the model results and the observed data, were used to determine model accuracy and precision, respectively.

Both calibrations of the Link-Node Model were used to develop baseline conditions, as well as four additional scenarios, with the purpose of investigating the impact of existing conditions and the effect of oxygen-demanding substances on DO concentrations in the DWSC. Each simulated scenario was based on the removal of one of the four main causes of DO depletion in the DWSC as identified by previous studies (Chen and Tsai, 2001; Foe et al., 2002; Gowdy and Grober, 2005; Lee and Jones-Lee, 2003) and included (i) modification of the DWSC geometry to reflect river widths and depths consistent with adjacent sections of the SJR, (ii) removal of oxygen-depleting loads from the Stockton Regional Water Quality Control Facility (RWCF), (iii) removal of oxygen-depleting loads from the upstream portion of the SJR, and (iv) removal of oxygen-depleting loads from tributaries and urban runoff directly discharging into the DWSC.

Excess net oxygen demand (ENOD) is a measure of the SJR's DO deficit below assimilative capacity in reference to a regulatory standard (Gowdy and Grober, 2005). ENOD was calculated for DO excursion events and the relative contribution of each scenario to low DO events in the DWSC was determined by a comparison of the results from the modeled scenario and the corresponding baseline ENOD and DO concentrations. Additionally, both calibrated models were used to simulate the effects of decreased exports from the SJR at the head of Old River by increasing the flow rate through the DWSC. Results for all scenarios were classified by water year in order to further investigate the effect of flow on DO concentrations.

Previously, the Central Valley Regional Water Quality Control Board (CVRWQCB) determined that the responsibility for reducing ENOD should be apportioned among the contributing factors as follows: 30 percent to the City of Stockton RWCF; 60 percent to non-point sources (discharges from irrigated land and those responsible for the maintenance of the DWSC) and 10 percent from unknown or minor sources (Gowdy and Grober, 2005). Since the publication of Gowdy and Grober (2005), the Stockton RWCF discharge permit has been modified and now includes a limit for ammonia (CVRWQCB, 2008). To meet the modified permitted effluent limits, the Stockton RWFC underwent major improvement projects that included construction of a nitrification facility.

The overall goals of the Link-Node Model analysis were to determine the relative contribution of DWSC geometry, mass loads from the upstream SJR, mass loads from urban tributaries and runoff, and mass loads from the Stockton RWCF to the low DO problem in the DWSC. Additionally, the model was used to explore the effect of increased river flows on mitigating low DO conditions in the DWSC. The use of the 2012 and 2013 model calibrations for providing a scientific foundation for the development and implementation of a DO TMDL for the SJR, based on using model results to assist with policy decisions and load allocation calculations, was investigated.

Methods

Description of Study Area

The study area comprises the downstream estuary portion of the SJR beginning at the junction with Old River near Mossdale and ending at Light 18 of the DWSC (Figure 1; Herr, et al., 2008). Flow in this area is affected by a 25 hour tidal cycle. Upstream of the DWSC, the RWCF discharges treated effluent from the City of Stockton into the SJR (Figure 1; Hallock et al., 1970; Gowdy and Grober, 2005).

Due to reoccurring low DO conditions in the DWSC which affect salmon migration and other aquatic life, the SJR has been placed on the federal 303(d) list of impaired water bodies under the Clean Water Act. The CVRWQCB was established a minimum 6 mg L^{-1} DO objective during the salmon migration months (September through November) in addition to a 5 mg L^{-1} DO standard during the remaining months (Gowdy and Grober, 2005; Lee and Jones-Lee, 2000). In 2005, the CVRWQCB adopted a control program to allocate responsibility for excess net oxygen demand (ENOD) above the DO criteria to the entities responsible for oxygen depletion due to the change in DWSC geometry, reduced flows through the DWSC, oxygen-depleting loads from the Stockton RWCF, and upstream non-point source pollution (CVRWQCB, 2011). The Stockton RWCF has since added a nitrification facility to comply with a cease and desist order from the CVRWQCB to satisfy the 2 mg L^{-1} NH_4^+-N average monthly effluent limitation and 5 mg L^{-1} NH_4^+-N maximum daily effluent limitation outlined in their National Pollution Discharge Elimination System (NPDES) permit (CA0079138). The nitrification facilities were online on September 18, 2006 (CVRWQCB, 2008).

Observed Dissolved Oxygen Data

Continuously monitored dissolved oxygen (DO) data for the SJR at RRI monitoring station (Figure 2) was obtained from available sources (CDEC, 2013). The DO data at this station was collected by the California Department of Water Resources (DWR) from January 1, 2005 to December 31, 2011 at a depth of 1 m, following DWR quality assurance and quality control (QA/QC) protocol. Since 2008 DO data has also been collected at depths of 3 and 6 m; however, only 1 m DO data was used here since it was available through the entire period of study. In the data set, DO measurements were taken at 15 minute intervals; however, to be consistent with flow measurement frequency, only DO data recovered within ±5 minutes of the hour was retained for this analysis. Where multiple DO measurements were made within the time period of ±5 minutes of the hour, the DO data was averaged.

Observed Flow Data

Continuously monitored flow data was obtained from available sources (CDEC, 2013) for the SJR at RRI and Garwood Bridge monitoring stations (Figure 2). Flow measurements at Garwood Bridge were collected every hour with more frequent measurements taken when anomalous "events" were occurring (CDEC, 2013). Flow data at this station was available from December 31, 2004 to September 1, 2011. Flow measurements at RRI were taken at the same frequency as Garwood Bridge; however, data was only available beginning January 9, 2007. Only flow data recovered on the hour was retained for this analysis. Where multiple flow measurements were made within the hour, the net flow rate at each hour was calculated.

Net flow rate was calculated by applying a moving average centered at each hour with averaging time intervals varying from 1 to 32 hours. Net flow rate is the difference between the volume of water flowing downstream and the volume of water flowing upstream during the specified time interval. Calculation of the net flow rate, rather than the flow rate, is essential in a tidally-influenced water body such as this. The results were plotted and the averaging time interval that resulted in the least amount of oscillation was selected. Using this technique, an averaging interval of 25 hr was selected.

Because flow data at the RRI monitoring station was limited, a linear regression analysis was developed to determine whether flow data from the Garwood Bridge station could be used to represent net flow through the DWSC. The analysis resulted in a good linear fit for net flow at the RRI and Garwood Bridge monitoring stations (R2=0.913; Figure 3) with the regression equation,

$$y = 105 + 0.953x \qquad (1)$$

where x is the net flow (cfs) at Garwood Bridge and y is the net flow (cfs) at RRI.

The non-negative y-intercept indicates that use of the Garwood Bridge data will result in the underprediction of flow rate at RRI by approximately 105 cfs. The mean net flow rates for the RRI and Garwood Bridge sites are 1,714 cfs and 1,415 cfs, respectively (Table 1). Based on the results of the linear regression analysis and given that the data set was complete, the Garwood Bridge net flow data was used here to represent net flow through the DWSC.

Model Overview

The Link-Node model simulates flow and water quality in the tidally influenced portion of the lower SJR between the junction with Old River and Light 18 of the DWSC (Herr, et al., 2008). The primary area of interest in this study is the SJR at RRI monitoring station which is located within the Stockton DWSC and is used for compliance monitoring, particularly for observing DO concentration (Node 40; Figure 1). Inputs to the Link-Node model include the upstream SJR (Node 1; Figure 1), urban tributaries (14-Mile Slough, Bear Creek, Mosher Slough, Calaveras River, Mormon Slough, Duck Creek, Littlejohns Creek, French Camp Slough, Pixley Slough, and Stockton urban runoff, all of which drain directly into the DWSC), and the Stockton RWCF outfall (between Node 25 and 26; Figure 1). Documentation of the model interface and the engineering algorithms that form the basis of the model are available in Chen and Tsai (2001, 2002).

Model Calibration

In November 2012, Systech Engineering calibrated the Link-Node model using observed DO data at the SJR at RRI monitoring station. This effort is referred to as the November_2012 model calibration throughout this report. In May 2013, the Link-Node model was again calibrated. The second calibration was based on the same DO data set but included improved wind data at RRI, more representative biochemical oxygen demand (BOD) decay rates, and an improved re-aeration adjustment factor to address concerns that the previous baseline scenario under-predicted DO concentrations and over-predicted the number of days where DO excursions occurred (Appendix 5.1.1, Sheeder and Herr, 2013). This effort is termed the May_2013 model calibration throughout this report.

Baseline Scenarios

Baseline scenarios for both the November_2012 and May_2013 model calibrations were simulated in order to predict the existing conditions within the Link-Node model domain. Observed data was used to define boundary conditions for the Link-Node model. This data included temperature, DO, chlorophyll a, and turbidity (used to estimate total suspended solids) from the SJR at Mossdale monitoring station, which was used to compile the input dataset for the upper portion of the SJR. In addition, water quality data for the Stockton RWCF tertiary effluent was characterized using measured data, as reported in the City's monthly monitoring reports as part of their compliance requirements for with their discharge permit.

Where observed data were unavailable, output from the Sacramento River version of the Watershed Analyses Risk Management Framework model (SAC-WARMF) was used to provide water quality input parameters for Stockton tributaries and urban runoff. Model output from the

SJR-WARMF-2008 model was not used as input for the Link-Node model and observed data were used to define the boundary conditions for the SJR river upstream of the estuary.

Assessment of Model Error

Model accuracy and precision were described using relative error and absolute error, respectively. Accuracy reflects the ability of the model to capture the central tendency of the observed data while precision describes the ability of the model to match the pattern of the data (Figure 4). The mean relative error, an estimate of model accuracy, is given by,

$$E_{rel} = \frac{1}{n}\sum_{i=1}^{n}(x_i - c_i) \tag{2}$$

where x is the model DO concentration (mg L^{-1}), c is the observed DO concentration (mg L^{-1}), and n is the number of data points. Relative error is calculated for the ith time step as $x_i - c_i$. For mean relative error, positive numbers indicate model over-prediction, negative numbers indicate model under-prediction, and numbers close to zero indicate good accuracy; for example, a mean relative error of 1.0 mg L^{-1} indicates that the model tends to over-predict DO concentrations by 1.0 mg L^{-1}. The mean absolute error, an estimate of model precision, is given by,

$$E_{abs} = \frac{1}{n}\sum_{i=1}^{n}|x_i - c_i| \tag{3}$$

For mean absolute error, numbers close to zero indicate good precision. Absolute error is calculated for the ith time step as $|x_i - c_i|$. A mean absolute error of 1.0 mg L^{-1} indicates that the model results tend to be 1.0 mg L^{-1} higher or lower than the observed DO concentrations. Note that it is possible to have a mean relative error of zero but a mean absolute error greater than zero; this can happen when the same amount of model over-prediction and under-prediction occurs. Both the mean relative error and mean absolute error can be expressed as percentages by dividing each by the mean observed concentration and multiplying the final result by 100%,

$$\%E_{rel} = \frac{1}{n}\sum_{i=1}^{n}\frac{x_i - c_i}{\bar{c}} \times 100\% \tag{4}$$

$$\%E_{abs} = \frac{1}{n}\sum_{i=1}^{n}\frac{|x_i - c_i|}{\bar{c}} \times 100\% \tag{5}$$

where $\bar{c}$ is the mean observed DO concentration (mg L^{-1}). This gives a representation of mean relative error and mean absolute error with respect to the original values; a mean relative error of 50% indicates that the model tends to over-predict observed DO concentrations by half of the original values while a mean absolute error of 50% indicates that the model results tend to be 50% higher or lower than each observed DO concentration.

Altered Load Scenarios

Using both the November_2012 and the May_2013 model calibrations, four additional scenarios were simulated to investigate the impact of oxygen-demanding substances on DO concentrations in the DWSC (herein termed "altered load scenarios"; Table 2). In each of the four scenarios, the input of a specific condition or source of oxygen consuming materials was eliminated to determine its individual effect on DWSC DO depletion. The effect of each scenario was evaluated by comparing the simulation results with the baseline results. The altered load scenarios were:

1. Elimination of the deepened Stockton Deep Water Ship Channel ("No DWSC" scenario) To assess the impact that dredging of the DWSC has on DO, the depth of Link-Node segments corresponding to the DWSC were changed from approximately 40 feet to 12.5 feet, the depth of the natural stream channel upstream of the dredged area.
2. Elimination of oxygen consuming materials flowing into the Link-Node domain from the SJR ("No SJR" scenario) To estimate the impact of SJR inflows on DO concentrations in the DWSC, the concentrations of oxygen consuming materials in the Link-Node boundary inflow file were reduced to zero. Oxygen consuming materials include BOD, ammonia-nitrogen, coliform bacteria, and Chlorophyll-a (used as a measure of algae).
3. Elimination of oxygen consuming materials flowing into the Link-Node domain from tributaries other than the SJR ("No Tribs" scenario) To estimate the impact of tributary inflows on DO concentrations in the DWSC, the concentrations of oxygen consuming materials in the Link-Node tributary inflow files for Stockton urban runoff and tributaries were reduced to zero. Oxygen consuming materials include BOD, ammonia-nitrogen, coliform bacteria, and Chlorophyll-a.
4. Elimination of oxygen consuming materials flowing into the Link-Node domain from the City of Stockton RWCF ("No RWCF" scenario) To assess the effect that this point source has on DO conditions in the DWSC, the concentrations of oxygen consuming materials in the Link-Node tributary inflow file, were reduced to zero. Oxygen consuming materials include BOD, ammonia-nitrogen, coliform bacteria, and Chlorophyll-a.

Allocating Oxygen-Consuming Load Sources

According to the 2005 Amendments to the Water Quality Control Plan for the Sacramento River and SJR Basins (Gowdy and Grober, 2005), when the DO concentration is below regulatory standards, the excess net oxygen demand (ENOD), a measure of the SJR's assimilative capacity, in lb day^{-1} is calculated by,

$$ENOD = \left(DO_{obj} - DO_{meas}\right) \times (Q_{DWSC} + 40) \times 5.4 \qquad (6)$$

where DO_{obj} is the DO criterion of 6 mg L^{-1} in the months of September through November and 5 mg L^{-1} during all other months, DO_{meas} is the measured DO concentration occurring in the SJR (mg L^{-1}), Q_{DWSC} is the 25 hour average net flow rate through the Stockton DWSC (cfs), 40 is an adjustment factor to account for flow measurement error, and 5.4 is a conversion factor. Positive ENOD values represents the net oxygen demand below the SJR's assimilative capacity based on the DO standard, while negative ENOD values represents the SJR's remaining assimilative capacity based on the DO standard. The ENOD is also positive when the net flow rate is negative and DO is above the criteria. Thus, only positive net flow values were considered and applied in this calculation. A margin of safety (MOS) is calculated based on the ENOD,

$$MOS = -0.2 \times ENOD \tag{7}$$

The total ENOD is divided into contributions from different sources,

$$ENOD - MOS = 1.2 \times ENOD = [\sum WLA + \sum LA] + R_{DWSC} + R_{Flow} \tag{8}$$

where $\sum WLA$ is the sum of waste load allocations resulting from point source pollution (lb day^{-1}), $\sum LA$ is the sum of load allocations resulting from non-point source pollution (lb day^{-1}), R_{DWSC} is the equivalent oxygen demand resulting from changes in channel geometry (lb day^{-1}), and R_{Flow} is the equivalent oxygen demand resulting from decreased net flow due to upstream diversions (lb day^{-1}).

Effect of Flow on Dissolved Oxygen Concentrations

Equation 8 for calculating the ENOD in the 2005 Basin Plan Amendments (CVRWQCB, 2011) includes the term R_{Flow} to represent the effective ENOD resulting from decreased flow in the impaired reach of the SJR. Analysis of the ENOD representing this term is difficult since changes in flow may also affect loads. It may not be realistic to have constant mass loads with variable flow rates. Therefore, the analysis of the effect of changing basin flow was analyzed separately from the other scenarios where mass load and ship channel geometry were altered.

To quantify the effect of flow on DO concentrations, Link-Node model scenarios were developed using the November_2012 and May_2013 model calibrations and the RRI observed DO data sets grouped by water year (Table 3). The water year starts on October 1 and ends on September 30 of the next calendar year. Using the DWR definitions for water years, classifications for wet years were coded as “wet”, classifications for above or below normal years were coded as “medium”, and classifications for dry and critical years were coded as “dry”. Table 3 contains a summary of the water year codes from 2005-2011 and their DWR water year classification equivalents (CDEC 2013).

In addition, the May_2013 model calibration was used to create an additional simulation called the Flow+500 cfs scenario. This scenario was used to simulate the effect of decreased exports from the SJR at the head of Old River by increasing flow in the Stockton DWSC by 500 cfs. This scenario was compared against the baseline scenario to evaluate whether increased flow in the DWSC would result in an improvement in DO and ENOD.

Results and Discussion

Evaluation of Model Calibrations

Addressing Gaps in Observed Data

In order to determine whether the model could be used to make predictions at times when observed data was unavailable (e.g. when measurements are missed due to equipment failure or malfunction), summary statistics were calculated for the entire prediction interval from January 1, 2005 through December 31, 2010 (Model Predictions; Table 4), as well as a subset of the predicted data including only predicted data points when simultaneous observed data was available (Model Predictions with Paired Observations; Table 4). The difference between the mean DO for all predicted data and for this subset of data was only 1.4%, indicating that predicted data did not seem to be compromised by gaps in observed data. Thus, the entire predicted datasets were used for all analyses included in this report.

Accuracy and Precision of Model Baselines

Summary statistics for the May_2013 and November_2012 model baseline scenarios are presented in Table 4. The mean predicted DO concentrations were 7.53 mg L^{-1} using the May_2013 model baseline scenario and 6.14 mg L^{-1} using the November_2012 model baseline scenario, indicating that the May_2013 model baseline scenario predicted higher DO concentrations than the November_2012 model baseline scenario.

The mean relative errors for DO calculated using the May_2013 and November_2012 model baseline scenarios were -0.110 mg L^{-1} and -1.49 mg L^{-1}, respectively (Table 5). This indicates an improvement in the accuracy when the May_2013 model baseline scenario was used compared to the results obtained when the November_2012 model baseline was used. The mean absolute error in predicted DO concentrations calculated using the May_2013 and November_2012 model baseline scenarios were 0.897 mg L^{-1} and 1.73 mg L^{-1}, respectively (Table 5). This shows that the changes made in the May_2013 model calibration, relative to the November_2012 model calibration, improved model output precision for the overall time period.

In order to visualize the accuracy and precision of the two model calibrations over time, a time series plot of the observed DO concentration at RRI, predictions obtained using the May_2013 model baseline scenario, and predictions obtained using the November_2012 model baseline scenario was used (Figure 5). Based on Figure 5, it appears that predictions obtained using both the May_2013 and November_2012 model baseline scenarios lacked precision in predicting large peaks and troughs in 2007 and 2008. This result was further analyzed by categorizing relative and absolute error by year (Figures 6 and 8, respectively) and month (Figures 7 and 9 respectively). The DO concentration calculated using the May_2013 model baseline scenario did have greater mean absolute error in 2007, while the November_2012 model baseline scenario produced a more accurate outcome for this year (Figure 8). Overall, however, results from the May_2013 model baseline scenario fared better, as indicated by the results for the mean relative and absolute error that did not vary greatly on a yearly or monthly basis (Figures 6-9).

Prediction of Dissolved Oxygen Excursions

Accuracy and precision of model predictions are particularly important at times when DO is below regulatory standards, referred to as DO excursions. For this reason, a separate analysis was performed on a subset of the predicted data, containing only data at times when excursions occurred (model predictions of DO excursions; Table 4). The mean predicted DO concentrations were 5.43 mg L^{-1} using the May_2013 model baseline scenario and 3.90 mg L^{-1} using the November_2012 model baseline scenario, indicating that the May_2013 model baseline scenario predicted higher DO concentrations than the November_2012 model baseline scenario during excursions.

DO excursions were observed at RRI on 286 days (13%) of the 6-year period occurring in 2005-2010, as compared with 102 days (5%) predicted using the May_2013 model baseline scenario and 665 days (30%) predicted using the November_2012 model baseline scenario (Table 6). The mean relative error for DO concentration calculated using the May_2013 model baseline scenario was 1.64 mg L^{-1} when RRI observed concentrations were below regulatory standards (Table 5), indicating that the model tended to over-predict DO concentrations during days when excursions occurred, and consequently, was less likely to predict excursions. The opposite appeared to be the case for the November_2012 model baseline scenario, which had a mean relative error of -0.321 mg L^{-1} when excursions occurred (Table 5), indicating that the model was under-predicting DO concentrations on days when excursions occurred.

In order to determine the accuracy of the two model calibrations in predicting DO excursions over time, the percent of days where excursions occurred was plotted by month for the May_2013 model baseline scenario (Figure 10) and the November_2012 model baseline scenario (Figure 11) (corresponding data is presented in Table 7). In addition, relative error was categorized on an annual (Figure 12) and monthly (Figure 13) basis. The May_2013 model baseline scenario under-predicted DO excursions in all years except 2009, while output from the November_2012 model baseline scenario over-predicts DO excursions in all years except in 2006 and 2007, when it under-predicts excursions (Figure 12). In both the May_2013 and November_2012 model baseline scenarios, the greatest over-predictions occurred in 2007 (Figure 12) as well as in the months of January and June (Figure 13) throughout the entire model simulation period. In order to determine the effect of flow on model prediction, mean percent excursion days were categorized by water year for observed RRI data and both model baseline scenarios (Figure 14). Based on this representation, the May_2013 model baseline scenario under-predicts excursions during dry and wet years, while the November_2012 model baseline scenario over-predicts excursions in medium years.

Oxygen Demand Sources

Dissolved Oxygen Improvement

Summary statistics for DO concentration in the DWSC as predicted by the four altered load scenarios are presented in Table 8. Time series plots of expected DO concentration improvement determined from the Link-Node model scenarios with respect to the model baseline scenario are shown in Figure 15 for the May_2013 model baseline and in Figure 16 for the November_2012 model baseline. The simulated restoration of the SJR depth to natural conditions in the DWSC and the simulated removal of loads originating from the SJR resulted in the greatest improvements in DO.

Summary statistics for DO concentration in the DWSC as predicted by the four altered load scenarios during DO excursions are presented in Table 9. Figures 17 and 18 show the mean, minimum, and maximum improvements in DO on each day where an excursion occurred for each of the Link-Node scenarios with the May_2013 and November_2012 model baselines with the largest daily DO deficit shown for comparison. Only the top 5% deficits for days with excursions are shown in Figure 18 due to the large number of excursion days predicted using the November_2012 model baseline. During the three day period April 24-27, 2006 there was an unusually large change in DO concentration from 7.77 mg L^{-1} on April 24 at 12:00 to 3.65 mg L^{-1} on April 25 at 16:00. This event appeared anomalous and the April 25, 2006 data was omitted from both figures. For both the May_2013 and November_2012 model baselines, the removal of the DWSC resulted in the greatest improvements in DO on days where excursions occurred.

Excess Net Oxygen Demand

Figures 19 and 20 show ENOD loads calculated using the May_2013 and November_2012 model baseline scenarios where DO excursions were predicted. For both model baselines, ENOD loads were highest in 2005 and 2009. Figure 20 includes more years than Figure 19 since Link-Node scenarios generated using the November_2012 model baseline resulted in prediction of more DO excursions than scenarios generated using the May_2013 model baseline. Summary statistics for ENOD were calculated for each Link-Node scenario (Table 10) and for each Link-Node scenario relative to the baseline (Table 11). The No DWSC and No SJR scenarios resulted in a higher number of predicted negative ENOD values compared with predictions generated for the other scenarios, indicating that removal of the DWSC and removal of oxygen-demanding loads from the SJR resulted in greater improvement in DO concentrations than removal of oxygen-demanding loads from the Stockton RWCF or oxygen-demanding loads from tributaries to the SJR.

Effects of Increased Flow through the Stockton DWSC

Daily Minimum DO versus Observed Net Flow

According to the 2005 Amendments to the Water Quality Control Plan for the Sacramento River and SJR basins, no DO excursions were observed between November 1995 and September 2000 when net flow through the DWSC exceeded 3000 cfs (Gowdy and Grober, 2005). With one exception on August 17, 2005, this also holds true for the time period between January 2005 and August 2011 (Figure 21).

Flow+500 cfs Scenario

The modeled 500 cfs flow increase resulted in a predicted improvement in the mean DO at RRI from 7.53 mg L^{-1} to 7.63 mg L^{-1} (1.3% increase) and a predicted improvement in minimum DO from 4.83 mg L^{-1} to 5.10 mg L^{-1} (5.6% increase) (Table 12). The mean ENOD decreased from -11,295 kg day^{-1} to -13,607 kg day^{-1} (20% decrease) while the maximum ENOD decreased from 2,414 kg day^{-1} to 2,400 kg day^{-1} (0.6% decrease) (Table 12). Increasing flow by 500 cfs over baseline reduced the total number of DO excursions by 48% from 2007 to 1036 and reduced the total number of days with DO excursion by 39%, from 102 to 62 (Table 13). Based on Figure 22, the increased flow appears to be most effective in improving DO between May and September during late spring and early fall; however, in some cases, the Flow+500 cfs scenario predicted lower DO concentrations than predicted in the baseline scenario, suggesting that increased flow alone may not completely resolve DO excursions without other management measures. The mean percentage of days per month with DO excursions in the baseline and Flow+500 cfs scenarios is shown in Figure 23. The percentage of days with excursion per month in the Flow+500 cfs scenario is about 5% lower than in the baseline scenario, indicating improvement. Since excursions were not predicted in the baseline scenario during the time periods in January through June and November through December, no conclusions can be drawn about the effectiveness of increasing flow on DO during these months (Figure 23). A comparison of ENOD for the baseline and Flow+500 cfs scenarios is presented in Figure 24; in many cases where the baseline ENOD was positive, increasing flow by 500 cfs gave a negative ENOD, indicating that the increased flow resolved excursions in the DWSC. However in some cases, the increase in flow had no effect on ENOD.

Recommendations for Future Model Investigations

Based on the result that the November_2012 and May_2013 model calibrations likely bracket the desired model accuracy for predicting excursions in the DO standard, it is recommended that a third model calibration be considered using a combination of both the November_2012 and the May_2013 model baseline coefficients to balance the risks and outcomes of model under-prediction and over-prediction. In addition, both the May_2013 model and November_2012 models yielded results that indicated difficulty in predicting days with excursions in 2007 and 2008. Both years were dry years that followed two wet years (in 2005 and 2006). While the flow conditions may have affected model precision, the mechanisms resulting in the altered DO concentration is not well understood. Improvement in model simulation results for these two years is recommended to further improve model precision and accuracy for predicting DO excursions.

In this analysis, the sum of the differences in ENOD and DO concentration were calculated between each Link-Node scenario and the baseline scenario, which indicates the amount of oxygen needed to restore the SJR to a state that is supportive of fish and other aquatic life. However, complex interactions exist between processes that produce and consume oxygen (such as re-aeration and reactions between nutrients), suggesting that the contributions of oxygen-consuming substances are not directly additive. One recommendation of this study is to conduct additional simulations using combinations of altered load scenarios, including a model run with all four loading sources removed to improve error quantification and to provide an estimate of the maximum possible DO improvement. In addition, investigations into the incremental improvement necessary to restore DO objectives are warranted. Separate scenarios with increased and decreased diversions are needed to quantify the effect of flow on DO concentrations. Scenarios with variable DWSC cross-sections would be beneficial for providing a better understanding of how hydraulic detention time affects DO concentrations and how future modifications could improve or worsen DO concentrations.

Evaluation of ENOD as an Indicator of Water Quality Impairment

In the 2005 Basin Plan Amendments (Gowdy and Grober, 2005), ENOD was proposed as a metric for evaluating low DO in the DWSC. Based on the current dataset, it is possible to compare DO and ENOD and determine if ENOD provides additional information beyond DO measurements and predictions. First, a review of ENOD is warranted. As previously stated, ENOD is the net oxygen demand over and above the assimilative capacity. The ENOD represents the DO deficit once the regulatory standard has been exceeded. As such, ENOD is only calculated when the measured DO is below the regulatory standard (Gowdy and Grober, 2005). In this report, we also calculated ENOD when the predicted DO for the simulated scenarios was above the regulatory standard so that we could evaluate the full benefit of the scenario beyond the regulatory standard.

$$\text{ENOD} = \left(DO_{obj} - DO_{meas}\right) \times (Q_{DWSC} + 40) \times 5.4 \qquad (6)$$

The calculation of ENOD in the 2005 Basin Plan Amendments is somewhat ambiguous, since the DO values to be used in the calculation are not explicitly stated. It is not clear if single measurements or values that are averaged over a time period should be applied in the calculation. Within the 2005 Basin Plan Amendments, hourly average DO concentration data is presented (see Table 4-1 on page 21), suggesting that hourly average data should be used. Currently, DO is measured at RRI for compliance and measurements are taken every 15 minutes. It is our understanding that violations of the objectives are based on single measurements and not on hourly averaged DO data. In this study, ENOD was calculated using single measurements taken at the hour.

The 2005 Basin Plan Amendments clearly state that flow through the DWSC should be calculated using a 25-hour moving average of flow since flow in the tidally influenced SJR is positive (flow direction is downstream) and negative (flow direction is upstream) on a daily basis. Use of the 25-hour moving average results in a net flow value that represents flow traveling downstream, as the tidal back-and-flow movement of the water is removed from the net flow value. At the flow monitoring stations on the SJR, hourly flow data is reported. We interpreted the Q_{DWSC} to mean that the 25-hour moving average should be centered over the time period for which it is calculated (Equation 9).

$$Q_{DWSC,t} = \frac{1}{25}\sum_{i=t-12}^{t+12} Q_{DWSC,i} \qquad (9)$$

As shown in Equation 9, $Q_{DWSC,t}$ is a 25-hour moving average, centered on the tth hour within the dataset. Interpreted as such, $Q_{DWSC,t}$ represents average 25-hour flow that represent average flow over a one-hour time period (the tth hour) even though it is reported in units of cfs. If hourly average DO measurements ($DO_{meas,t}$) and hourly average $Q_{DWSC,t}$ calculations are used to calculate ENOD (Equation 6), the ENOD values will represent hourly average ENOD values.

Further, the 2005 Basin Plan Amendments does not address how negative net flow should be handled in the ENOD calculation. In this report we only included positive net flow in the ENOD calculations. However, it could be argued that negative and positive flow values should be included since low DO waters will likely be problematic for migrating fish, regardless of which direction the river is flowing. In the SJR, the net flow can be negative if river exports exceed river inputs (e.g. from dam releases and agricultural return flows). In the current dataset, negative net flow was calculated for 3,509 of the hourly increments. Flow data were available for 46,497 of the hourly increments, demonstrating that negative net flow occurred 7.5% of the time. To calculate ENOD occurring over a single calendar day with consideration for positive and negative net flow, Equation 10 should be used.

$$\text{ENOD} = \frac{1}{24}\sum_{t=1}^{24}\left(DO_{obj} - DO_{meas,t}\right) \times \left(\left|Q_{DWSC,t}\right| + 40\right) \times 5.4 \qquad (10)$$

Equation 10 is also an improved ENOD calculation to represent daily ENOD (compared to Equation 6) since the ENOD (triggered by a violation) may not occur over all 24 hours of a day. If violations occur over all 24 hours of a day, the average of those 24 values will yield the same results as Equation 10. However, if violations do not occur over all 24 hours of the day and an average of the ENOD values is calculated rather than using Equation 10, daily ENOD will be over-estimated.

It should be noted that calculation of ENOD requires measurement of both flow and DO, making it more difficult to use this as a regulatory metric instead of DO concentration alone. When continuous monitoring is used, data are unavailable in the event of equipment failure or malfunction. Also, extremely high or low flow events and changing river conditions may require adjustment of rating curves used in flow measurements. In the dataset used here, there are 52,511 hourly increments and flow data were available for 46,497 of these increments (11% missing) and DO data were available for 51,434 of these increments (4% missing). So, flow and DO data were available for most of the dataset. Of the 79 days where DO violations were predicted by the model and observed flow data were available, DO violations occurred over all 24 hours of the day for 43 of the 79 days. For the other 36 days, DO violations did not occur over all 24 hours, making it more accurate to use Equation 10 to calculate daily ENOD.

An advantage to using ENOD over DO concentration is that the volume of the impaired water is estimated and not just that a violation occurred. When predicted ENOD is compared with predicted DO, it is apparent that for a given DO concentration, there are varying amounts of ENOD based on different flow conditions. The volume of low DO water is important because it indicates the extent of low DO, and more importantly, the amount of effort needed to correct the water quality impairment. Estimates of ENOD are especially important if supplemental aeration is used to mitigate low DO. The maximum hourly and daily ENOD values can be used to design aeration systems. The hourly ENOD data may be especially useful for determining how to operate aeration systems to accommodate the diurnal fluxuations in low DO.

Use of flow in addition to DO to indicate the volume of low DO river water appears advantageous, but it does have some limitations when it is applied with monitoring occurring at a single point. If net flow is sufficiently high, it will be possible to identify an entire “slug” of low

DO water as it travels past the monitoring point. However, if net flow is at or near zero, it will not be possible to determine the volume of impaired river water (using the ENOD calculation in Equation 10) because it will be stagnant within the ship channel. Surveys of DO completed throughout the DWSC indicate that when low DO is occurring, it tends to be widely spread throughout the DWSC and not isolated (Schmieder et al., 2008; Spier et al., 2013). To further confirm low DO and obtain a better volumetric estimate of the river affected by low DO, it may be warranted to consider additional DO monitoring stations in the DWSC. The data from the multiple stations would need to be evaluated in a manner such that a three-dimensional estimate of DO deficit is obtained. Since 2008 DO measurements have been taken at three depths (1, 3, and 6 m depth) at the RRI compliance station, giving a better representation of DO throughout the depth of the DWSC. Computer modeling could be used to estimate the volume of low DO water in the DWSC at any given time, provided that the model is calibrated for that time period. The Link-Node model is configured to give such estimates, since it is developed based on a series of linked completely-mixed reactors.

Conclusions

The May_2013 model baseline demonstrated improved accuracy and precision in comparison with the November_2012 model baseline, but it had less accuracy in predicting DO concentration on days when the observed concentration were below regulatory standards. While the November_2012 model tended to under-predict DO concentration, the May_2013 model tended to over-predict it. The latter situation results in less conservative predictions. The risk is that model predictions obtained using the May_2013 model baseline may predict compliance based on implementation of load-reducing strategies that may not be realized when the strategies are actually implemented. However, it appears that use of the two model baseline scenarios provides valuable information that gives a range of DO concentrations for any given year, given a range of net flow rates expected in any given year, which enhances the model output and its potential use as a planning and management tool. An additional model calibration is recommended that uses a combination of model coefficients from both of the existing model scenarios to balance the risks and accuracy of model prediction.

The two calibrated models, November_2012 and May_2013, were used to simulate four scenarios where distinct oxygen-depleting loads were removed in each Link-Node model scenario. While reduced oxygen-depletion occurred in each of the scenarios, indicating the relative impact of each contributing source, the results suggest that the relative contributions are not evenly distributed, regardless of which model calibration was used. The results of the model scenarios contained in this study suggest that re-allocation of oxygen-demanding loads should be considered. While preliminary, the model simulations results presented here indicate that the contribution of oxygen-demand from the DWSC may be more significant than previously thought in relation to oxygen-demanding loads from the SJR. The model results also suggest that the relative contributions of the RWCF and the urban tributaries are less significant than the contributions from the DWSC and the SJR. However, it is important to note that the contributions of oxygen-consuming substances are not directly additive. Additional model simulations using combinations of the altered load scenarios is recommended in order to further investigate the complex interactions between processes that produce and consume oxygen.

Increased flow through the DWSC, as predicted by the Flow+500 cfs scenario using the May_2013 model calibration, resulted in overall improved DO conditions in the DWSC including decreasing low DO excursions by nearly half. However in some cases, the Flow+500 cfs scenario forcasted worse DO concentrations than the baseline scenario, suggesting that moderate increases in flow alone will not completely resolve DO excursions without other management measures. A stepwise analysis of diversions from the SJR is recommended to further investigate the effects of flow on the DO conditions in the DWSC.

All scenarios resulted in improvement in DO and in a decreased number of violations predicted. During the study period, violations were observed at RRI for 13% of hourly recorded data, while violations were predicted for 5% of the hourly predictions in the May_2013 baseline model. In the May_2013 baseline model, violations were predicted for 2007 hours during the six year observation period, and these violations were predicted to occur on 102 days within that time period. Relative to the May_2013 model baseline, the “No DWSC” had 62% fewer predictions of hourly violations while the predicted improvement was 52% for the “No SJR” scenario, relative to the model baseline. The “No RWCF” and “No Tribs” scenarios resulted in 36% and 12% fewer predicted hourly violations relative to the baseline model. On a daily basis, the “No DWSC” scenario resulted in 56% fewer days where violations were predicted by the May_2013 model, while the “No SJR” scenario resulted in 43% fewer days where violations were predicted. The “No RWCF” and “No Tribs” scenarios resulted in 29% and 16% fewer predicted days with violations relative to the baseline model. If the number of hourly violations predicted for each scenario is subtracted from the number of hourly violations predicted using the model baseline, the responsibility of each contributing factor can be estimated. The result is that 1247 predicted hourly violations are attributed to the DWSC (38%), 1039 are attributed to the ODS from the SJR (32%), 723 are attributed to the ODS from the RWCF (22%), and 241 are attributed to the ODS from the urban tributaries (7%). These results are based on observations and the Link-Node model that was calibrated for the six year time period 2005 to 2011.

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References

California Data Exchange Center (CDEC). 2013. California Data Exchange Center – River Stages / Flow. Accessed at: http://wwwcimis.water.ca.gov/cimis/data.jsp, California Department of Water Resources, Sacramento, CA.

California Regional Water Quality Control Board Central Valley Region (CVRWQCB) (2008). Waste Discharge Requirements for the City of Stockton Regional Wastewater Control Facility San Joaquin County, NPDES No. CA0079138, Rancho Cordova, CA.

California Regional Water Quality Control Board Central Valley Region (CVRWQCB) (2011). The Water Quality Control Plan (Basin Plan) for the California Regional Water Quality Control Board Central Valley Region Fourth Edition. Sacramento, CA.

Chen, W.C., and W. Tsai (2001). Improvements and Calibrations of Lower SJR DO Model. Systech Engineering, Inc., San Ramon, CA.

Chen, W.C., and W. Tsai (2002). User's Manual: San Joaquin River Dissolved Oxygen Model. Prepared for: CALFED 2000 Grant, CALFED 99-B16, DWR 4600000989, Systech Engineering, Inc., San Ramon, CA.

Foe, C., M. Gowdy, and M. McCarthy (2002). Strawman Source and Linkage Analysis for Low Dissolved Oxygen in the Stockton Deep Water Ship Channel. California Regional Water Quality Control Board. Sacramento, CA.

Gowdy, M. and Grober (2005). Amendments to the Water Quality Control Plan for the Sacramento River and SJR Basins. California Environmental Protection Agency, Rancho Cordova, CA.

Hallock, R.J., R.F. Elwell, and D.H. Fry Jr. (1970). Migrations of Adult King Salmon Oncorhynchus tshawytscha in the San Joaquin Delta as Demonstrated by the Use of Sonic Tags. Department of Fish and Game, Fish Bulletin 151: 1-92.

Herr, J., C.W. Chen, and K. van Werkohven (2008). Final Report for the Task 6 Modeling of the SJR. Prepared for: CALFED Project ERP-02D-P63, Systech Engineering, Inc., Walnut Creek, CA.

Herr, J., L. Weintraub, and C.W. Chen (2000). User's Guide to WARMF: Documentation of Graphical User Interface, Prepared for: Electric Power Research Institue, Systech Engineering, Inc., San Ramon, CA.

Lee, G.F. and A. Jones-Lee (2000). Issues in Developing the SJR Deep Water Ship Channel DO TMDL. G. Fred Lee & Associates, El Macero, CA.

Schmieder, P.J., D.T. Ho, P. Schlosser, J.F. Clark, and S.G. Schladow (2008). An SF6 Tracer Study of the Flow Dynamics in the Stockton Deep Water Ship Channel: Implications for Dissolved Oxygen Dynamics. Estuaries and Coasts 31: 1038–1051.

Sheeder, S., and J. Herr (2013). Calibration of the Link-Node Model for Application to Understanding Causes of Low Dissolved Oxygen Conditions in the Stockton Deep Water Ship Channel. Walnut Creek, CA.

Spier, C., J. Hanlon, M. Jue, A. Stubblefield, and W. Stringfellow. (2013) High Resolution Dissolved Oxygen Profiling of the Stockton Deep Water Shipping Channel during the Summer of 2012. San Joaquin River Dissolved Oxygen (DO) Total Maximum Daily Load (TMDL) Project E0883006. University of the Pacific, Stockton, CA.

Stringfellow, W., S. Borglin, J. Hanlon, J. Graham, R. Dahlgren, R. Burkes, C. Spier, T. Letain, K. Hutchinson, and A. Granadosin (2008). Task 4: Monitoring Study, Final Task Report. San Joaquin River Up-Stream DO TMDL Project ERP-02D-P63. University of the Pacific, Stockton, CA.

Table 1. Summary statistics for the San Joaquin River at Rough & Ready Island (RRI) and Garwood Bridge positive net flow rate from February 1, 2007 to August 31, 2011. Net flow rate was calculated from California Data Exchange Center (CDEC) data using a 25-hour moving average centered on each hourly data point.

	Net Flow Rate (cfs)	
	RRI	Garwood Bridge
Observations	31,517	36,414
Mean	1,714	1,415
Minimum	0.08	0.04
Maximum	11,646	12,198
Std. Dev.	2,044	2,038

Table 2. Description of the Link-Node scenarios simulated using the May_2013 and November_2012 model calibrations for the time period from January 1, 2005 to December 31, 2010.

Model Baseline Scenario	Scenario Names	Modification to Baseline
May_2013	Baseline	---
	No DWSC	Stockton DWSC removed
	No RWCF	Stockton RWCF removed
	No SJR	Oxygen-consuming loads from upstream SJR removed
	No Trib	Oxygen-consuming loads from tributaries removed
	Flow+500 cfs	Flow diverted from SJR at head of Old River decreased to increase flow through Stockton DWSC by 500 cfs
November_2012	Baseline	---
	No DWSC	Stockton DWSC removed
	No RWCF	Stockton RWCF removed
	No SJR	Oxygen-consuming loads from upstream SJR removed
	No Trib	Oxygen-consuming loads from tributaries removed

Table 3. San Joaquin Valley water year classification codes for data analysis. Each water year starts on October 1 and ends on September 30 of the following year (DWR 2013).

Water Year	**Classification**	**Type**	**Code**
2005	W	Wet year	Wet
2006	W	Wet year	Wet
2007	C	Critical year	Dry
2008	C	Critical year	Dry
2009	D	Dry year	Dry
2010	AN	Above normal year	Medium
2011	W	Wet year	Wet

Table 4. Summary statistics for the San Joaquin River at Rough & Ready Island (RRI) observed dissolved oxygen (DO) data and model output for the Link-Node model baseline scenarios using the May_2013 and November_2012 model calibrations for all model output and observed data occurring at, or approximately close to whole hour increments from January 1, 2005 to December 31, 2010. Predicted data is separated by whole data sets and subsets of predicted data including only predicted data during times when observed data is also available (model prediction with paired observations) and predicted data only during days when DO excursions are predicted (model predictions of DO excursions).

		No. of Results	Mean DO (mg L^{-1})	Min DO (mg L^{-1})	Max DO (mg L^{-1})	Std. Dev. DO (mg L^{-1})
RRI Observed Data	Obseved Data	50,434	7.63	1.8	13.7	1.68
May_2013 Model Baseline Scenario	Model Predictions	52,511	7.53	4.83	10.2	1.13
	Model Predictions with Paired Observations	50,434	7.52	4.83	10.2	1.14
	Model Predictions of DO Excursions	2,007	5.43	4.83	6	0.338
November_2012 Model Baseline Scenario	Model Predictions	50,541	6.14	1.44	10.3	1.78
	Model Predictions with Paired Observations	50,434	7.63	1.8	13.7	1.68
	Model Predictions of DO Excursions	15,422	3.9	1.44	6	1.04

Table 5. Error analysis for the Link-Node model output generated using the May_2013 and November_2012 model baseline scenarios from January 1, 2005 to December 31, 2010, for all days with complete hourly data and only when hourly San Joaquin River at Rough & Ready Island (RRI) observed dissolved oxygen (DO) concentration were below the 6 mg L^{-1} standard during September, October, and November, or below 5 mg L^{-1} during all other months.

		Mean Relative Error (mg L^{-1})	**Mean Absolute Error (mg L^{-1})**	**Mean Relative Error**	**Mean Absolute Error**
All Days	May_2013 Model Baseline	-0.11	0.897	-1.4%	12%
	November_2012 Model Baseline	-1.49	1.73	-20%	23%
Only Days with Excursions	May_2013 Model Baseline	1.64	1.72	22%	23%
	November_ 2012 Model Baseline	-0.32	1.8	-4.2%	24%

Table 6. Number of days with dissolved oxygen (DO) excursions for the San Joaquin River (SJR) at Rough & Ready Island (RRI) based on observed data and Link-Node model output obtained using the May_2013 and November_2012 model baseline scenarios for the time period from January 1, 2005 to December 31, 2010. See Table 2 for scenario descriptions. Excursions occur when the DO is below the 6 mg L^{-1} standard during September, October, and November, or below 5 mg L^{-1} during other months.

	No. of Days with Excursions	Percent of Days with Excursions
RRI	286	13%
May_2013 Model Baseline Scenario	102	5%
Nov_2012 Model Baseline Scenario	665	30%

Table 7. Comparison of observed dissolved oxygen (DO) excursions in the San Joaquin River at Rough & Ready Island (RRI) and DO excursions predicted by the Link-Node model obtained using the May_2013 model baseline scenario for all hourly data. Excursions occur when the dissolved oxygen (DO) concentration is below the 6 mg L^{-1} standard during September, October, and November, or below 5 mg L^{-1} during other months.

Year	Month	No. of Observed RRI DO Measurements	No. of Predicted Model DO Values	No. of Observed RRI DO Excursions	No. of Predicted Model DO Excursions	Observed RRI DO Excursions (%)	Predicted Model DO Excursions (%)
2005	1	693	744	5	0	0.7	0
	2	669	672	0	0	0	0
	3	714	744	0	0	0	0
	4	716	720	0	0	0	0
	5	575	744	0	0	0	0
	6	482	720	0	0	0	0
	7	693	744	48	0	6.9	0
	8	681	744	198	0	29.1	0
	9	716	720	546	681	76.3	94.6
	10	731	744	84	55	11.5	740.0
	11	711	720	77	0	10.8	0
	12	736	744	2	0	30.0	0
2006	1	547	744	0	0	0	0
	2	664	672	0	0	0	0
	3	699	744	0	0	0	0
	4	626	720	0	17	0	2.4
	5	683	744	0	0	0	0
	6	700	720	0	0	0	0
	7	734	744	128	0	17.4	0
	8	689	744	12	0	1.7	0
	9	611	720	2	0	30.0	0
	10	741	744	0	0	0	0
	11	706	720	0	0	0	0
	12	733	744	0	0	0	0
2007	1	726	744	0	0	0	0
	2	635	672	0	0	0	0
	3	587	744	0	0	0	0
	4	707	720	0	0	0	0
	5	729	744	0	0	0	0
	6	713	720	482	0	67.6	0
	7	736	744	622	0	54.5	0
	8	694	744	305	0	43.9	0
	9	710	720	432	0	60.8	0
	10	673	744	0	0	0	0
	11	582	720	0	0	0	0
	12	740	744	0	0	0	0

Table 7. continued

Year	Month	No. of Observed RRI DO Measurements	No. of Predicted Model DO Values	No. of Observed RRI DO Excursions	No. of Predicted Model DO Excursions	Observed RRI DO Excursions (%)	Predicted Model DO Excursions (%)
2008	1	741	744	0	0	0	0
	2	678	696	0	0	0	0
	3	690	744	0	0	0	0
	4	711	720	0	0	0	0
	5	701	744	0	0	0	0
	6	712	720	28	0	3.9	0
	7	744	744	1	0	0.1	0
	8	744	744	0	0	0	0
	9	715	720	156	178	21.8	24.7
	10	743	744	170	0	22.9	0
	11	718	720	0	0	0	0
	12	624	744	0	0	0	0
2009	1	744	744	0	0	0	0
	2	670	672	0	0	0	0
	3	743	744	0	0	0	0
	4	720	720	0	0	0	0
	5	743	744	29	0	3.9	0
	6	718	720	11	0	1.5	0
	7	744	744	2	87	0.3	11.7
	8	743	744	0	66	0	8.9
	9	719	720	269	720	37.4	100.0
	10	743	744	0	220	0	29.6
	11	720	720	0	0	0	0
	12	731	744	0	0	0	0
2010	1	740	744	0	0	0	0
	2	667	672	0	0	0	0
	3	744	744	0	0	0	0
	4	720	720	0	0	0	0
	5	743	744	0	0	0	0
	6	719	720	0	0	0	0
	7	744	744	90	0	12.1	0
	8	743	744	33	0	4.4	0
	9	720	720	131	0	18.2	0
	10	742	744	154	0	20.8	0
	11	719	720	0	0	0	0
	12	744	744	0	0	0	0

Table 8. Summary statistics for the San Joaquin River (SJR) at Rough & Ready Island (RRI) observed dissolved oxygen (DO) data and model output for the Link-Node model scenarios using the May_2013 and November_2012 model baseline scenarios for all model output and observed data occurring at, or approximately close to whole hour increments from January 1, 2005 to December 31, 2010. See Table 2 for scenario descriptions.

		No. of Results	Mean DO (mg L^{-1})	Min DO (mg L^{-1})	Max DO (mg L^{-1})	Std. Dev. DO (mg L^{-1})
May_2013 Model Baseline Scenario	Baseline	52,511	7.53	4.83	10.2	1.13
	No DWSC	52,511	8.03	4.94	10.9	1.15
	No RWCF	52,511	7.63	4.91	10.4	1.12
	No SJR	52,511	8.19	4.9	11.1	1.24
	No Tribs	52,511	7.61	4.93	10.3	1.13
November_2012 Model Baseline Scenario	Baseline	50,541	6.14	1.44	10.3	1.78
	No DWSC	50,541	7.54	3.72	10.6	1.36
	No RWCF	50,541	6.28	1.55	10.4	1.76
	No SJR	50,541	7.23	2.12	10.8	1.82
	No Tribs	50,541	6.31	1.74	10.4	1.75

Table 9. Summary statistics for the San Joaquin River at Rough & Ready Island (RRI) Link-Node model output for dissolved oxygen (DO) obtained using the May_2013 and November_2012 model baseline scenarios when the model predicted excursions. See Table 2 for scenario descriptions. Excursions occur when the dissolved oxygen (DO) concentration is below the 6 mg L^{-1} standard during September, October, and November, or below 5 mg L^{-1} during other months.

		No. of Results	Mean DO (mg L^{-1})	Min DO (mg L^{-1})	Max DO (mg L^{-1})	Std. Dev. DO (mg L^{-1})
May_2013 Model Baseline Scenario	Baseline	2,007	5.43	4.83	6	0.338
	No DWSC	2,007	6.08	5.16	7.16	0.533
	No RWCF	2,007	5.68	4.91	6.59	0.488
	No SJR	2,007	5.85	4.9	7.18	0.541
	No Tribs	2,007	5.53	4.93	6.12	0.329
November_2012 Model Baseline Scenario	Baseline	15,422	3.9	1.44	6	1.04
	No DWSC	15,422	5.93	3.72	8.26	0.869
	No RWCF	15,422	4.08	1.55	6.43	1.05
	No SJR	15,422	5.07	2.12	7.84	1.32
	No Tribs	15,422	4.11	1.74	6.27	0.991

Table 10. Summary statistics for excess net oxygen demand (ENOD) for each Link-Node model scenario generated using the May_2013 and November_2012 model baseline scenarios to predict dissolved oxygen (DO) excursions. Excess net oxygen demand (ENOD) was not calculated for net flows equal to or less than zero. Negative ENOD values represent resolution of DO deficit beyond the assimilative capacity such that the DO concentration is above the regulatory standard.

		No. of Results	Mean (kg d^{-1}) (alt. lb d^{-1})	Min (kg d^{-1}) (alt. lb d^{-1})	Max (kg d^{-1}) (alt. lb d^{-1})	St Dev (kg d^{-1}) (alt. lb d^{-1})
May_2013 Model Baseline Scenario	Baseline	1,171	767 (1,692)	0.182 (0.402)	4,924 (10,857)	695 (1,533)
	No DWSC	1,171	-386 (-852)	-5,350 (-11,797)	2,648 (5,838)	1,211 (2,671)
	No RWCF	1,171	401 (884)	-3,063 (-6,753)	4,389 (9,677)	1,023 (2,255)
	No SJR	1,171	-162 (-357)	-5,768 (-12,719)	4,254 (9,380)	1,491 (3,288)
	No Tribs	1,171	617 (1,361)	-361 (-796)	4,348 (9,587)	644 (1,421)
November_2012 Model Baseline Scenario	Baseline	11,322	2,012 (4,436)	0.0989 (0.218)	21,070 (46,460)	2,090 (4,608)
	No DWSC	11,322	-680 (-1,499)	-12,345 (-27,221)	7,029 (15,498)	1,399 (3,085)
	No RWCF	11,322	1,725 (3,804)	-1,935 (-4,267)	20,320 (44,806)	1,831 (4,038)
	No SJR	11,322	164 (361)	-15,327 (-33,795)	18,868 (41,604)	1,969 (4,342)
	No Tribs	11,322	1,770 (3,902)	-668 (-1,474)	19,731 (43,506)	1,952 (4,304)

Table 11. Summary statistics of the difference between the excess net oxygen demand (ENOD) from January 1, 2005 through December 31, 2010 for the model baseline and for the Link-Node scenario for each Link-Node model scenario generated using the May_2013 and November_2012 model baseline scenarios to predict dissolved oxygen (DO) excursions. These values represent the predicted improvement (reduced ENOD) for the scenarios relative to the baseline. Excess net oxygen demand (ENOD) was not calculated for net flows equal to or less than zero.

		No. of Results	Mean (kg d^{-1}) (alt. lb d^{-1})	Min (kg d^{-1}) (alt. lb d^{-1})	Max (kg d^{-1}) (alt. lb d^{-1})	St Dev (kg d^{-1}) (alt. lb d^{-1})
May_2013 Model Baseline Scenario	No DWSC	1,171	1,154 (2,544)	28.4 (62.6)	6,105 (13,461)	1029 (2,270)
	No RWCF	1,171	366 (808)	6.26 (13.8)	4,225 (9,316)	720 (1,588)
	No SJR	1,171	929 (2,049)	9.12 (20.1)	5,971 (13,166)	1,268 (2,795)
	No Tribs	1,171	150 (331)	7.48 (16.5)	637 (1,405)	89.8 (198)
November_2012 Model Baseline Scenario	No DWSC	11,322	2,692 (5,935)	63.9 (141)	26,430 (58,278)	2,204 (4,860)
	No RWCF	11,322	287 (633)	4.15 (9.15)	7,224 (15,928)	668 (1,474)
	No SJR	11,322	1,849 (4,076)	14.2 (31.3)	16,673 (36,763)	1,976 (4,357)
	No Tribs	11,322	243 (535)	11.3 (24.9)	1,857 (4,094)	169 (372)

Table 12. Summary statistics for dissolved oxygen (DO), positive net flow, and Excess Net Oxygen Demand (ENOD) for the baseline scenario and Flow+500 cfs scenario for the May_2013 Link-Node model calibration. Negative ENOD values represent resolution of DO deficit beyond the assimilative capacity such that the DO concentration is above the regulatory standard.

		Number of Predictions	**Mean**	**Min**	**Max**	**Standard Deviation**
Dissolved Oxygen (mg L^{-1})	Baseline	52,511	7.53	4.83	10.2	1.13
	Flow+500	52,511	7.63	5.1	10.3	1.08
Positive Net Flow (cfs)	Baseline	49,269	1,687	0.024	18,764	2,312
	Flow+500	52,443	2,058	0.296	19,230	2,281
Excess Net Oxygen Demand kg d^{-1} (lb d^{-1})	Baseline	49,269	-11,295 (-24,905)	-194,968 (-429,905)	2,414 (5,322)	17,824 (39,303)
	Flow+500	52,443	-13,607 (-30,003)	-199,803 (-440,565)	2,400 (5,292)	18,133 (39,983)

Table 13. Number of simulated excursions and days with dissolved oxygen (DO) excursions for the baseline and Flow+500 cfs scenarios using the May_2013 Link-Node model calibration.

	Excursions	Days with Excursions	% Excursions	% Days with Excursions
Baseline	2,007	102	3.8	4.7
Flow + 500 cfs	1,036	62	2	2.8

Figure 1. Link-Node model domain from Chen and Tsai (2002). The San Joaquin River at Rough & Ready Island is denoted by Node 40. The Stockton RWCF discharge into the San Joaquin River occurs between Node 25 and Node 26 in the model.

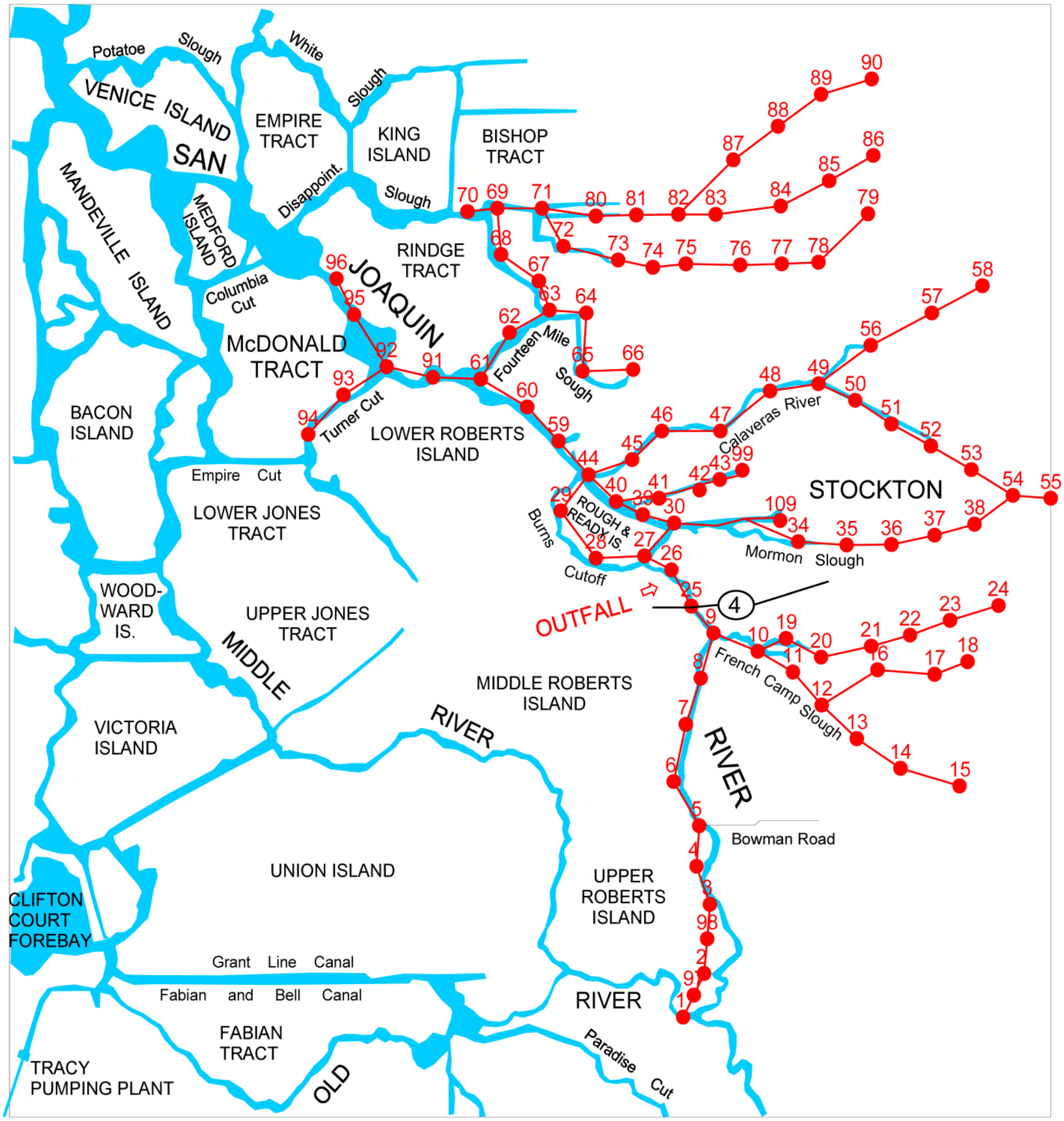


Figure 2. Locations where observed data was obtained between January 1, 2005 to December 31, 2010. Dissolved oxygen data was obtained at the Rough and Ready Island (RRI) Monitoring Station. Flow data was obtained at the RRI and San Joaquin River at Garwood Bridge monitoring stations.

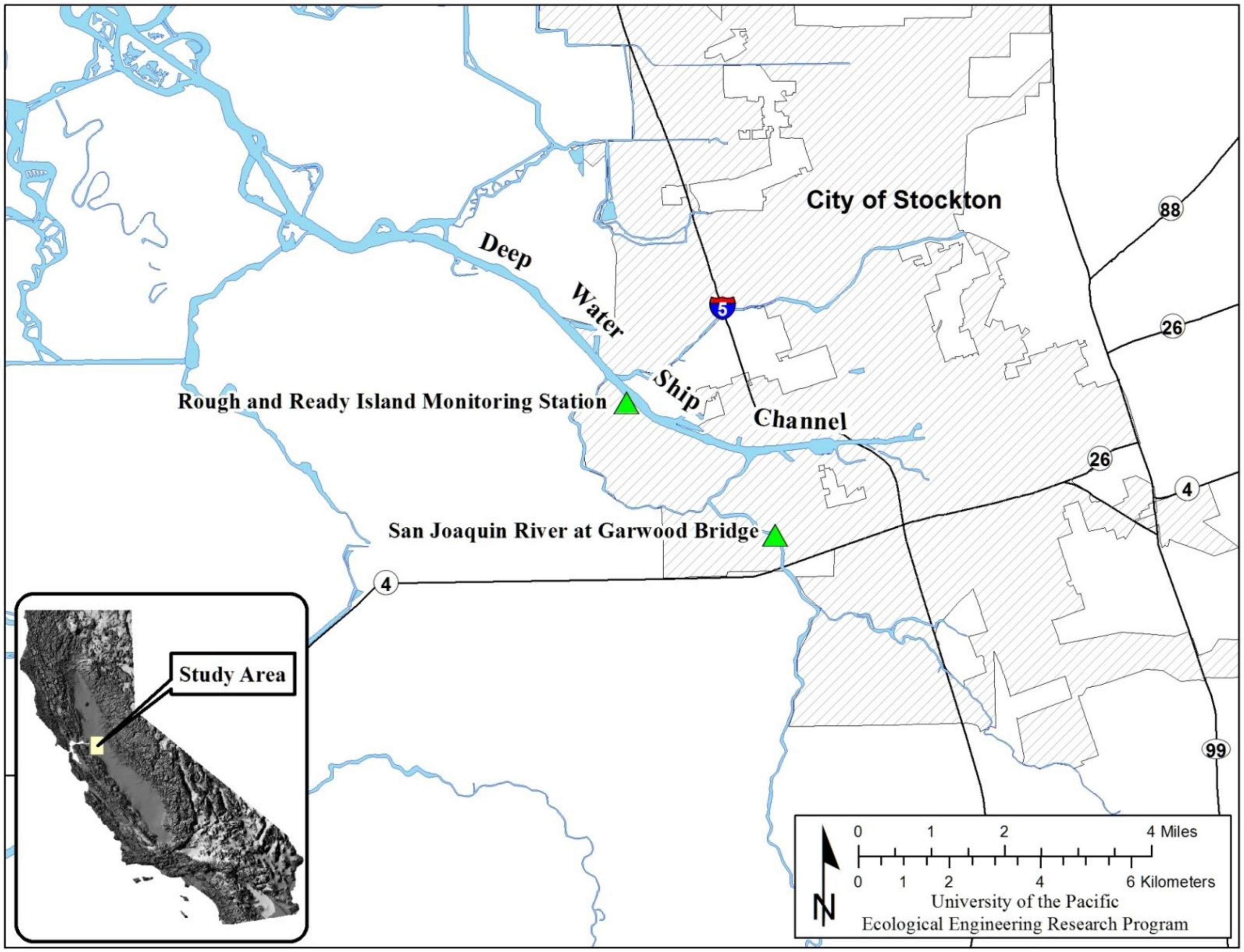


Figure 3. Relationship between San Joaquin River net flows at Rough & Ready Island (RRI) and at Garwood Bridge from February 1, 2007 through August 31, 2011.

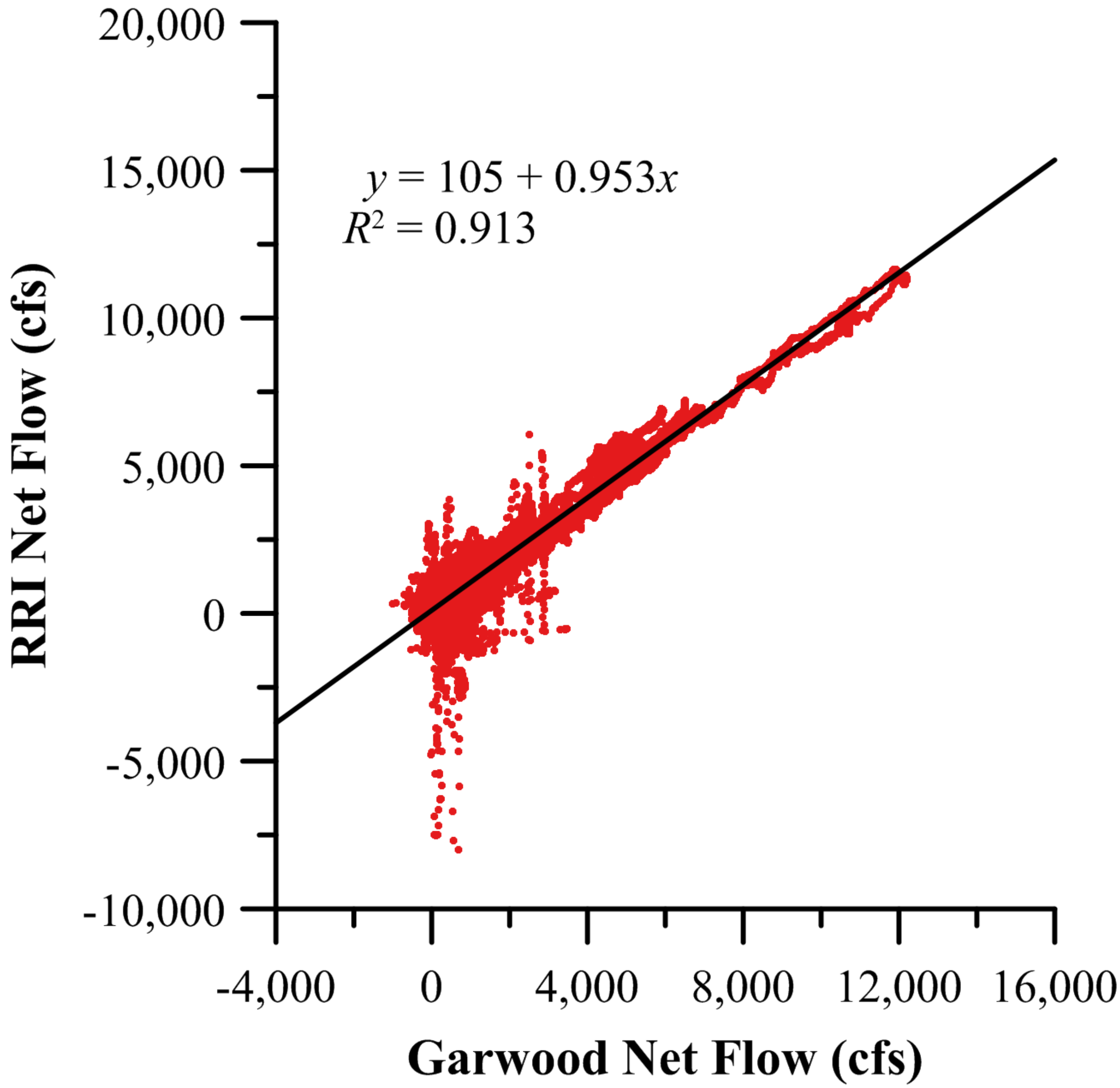


Figure 4. A demonstration of the difference between accuracy and precision. Accuracy describes the tendency of the model to underpredict or overpredict the observed data while precision describes the ability of the model to match the pattern of the data.

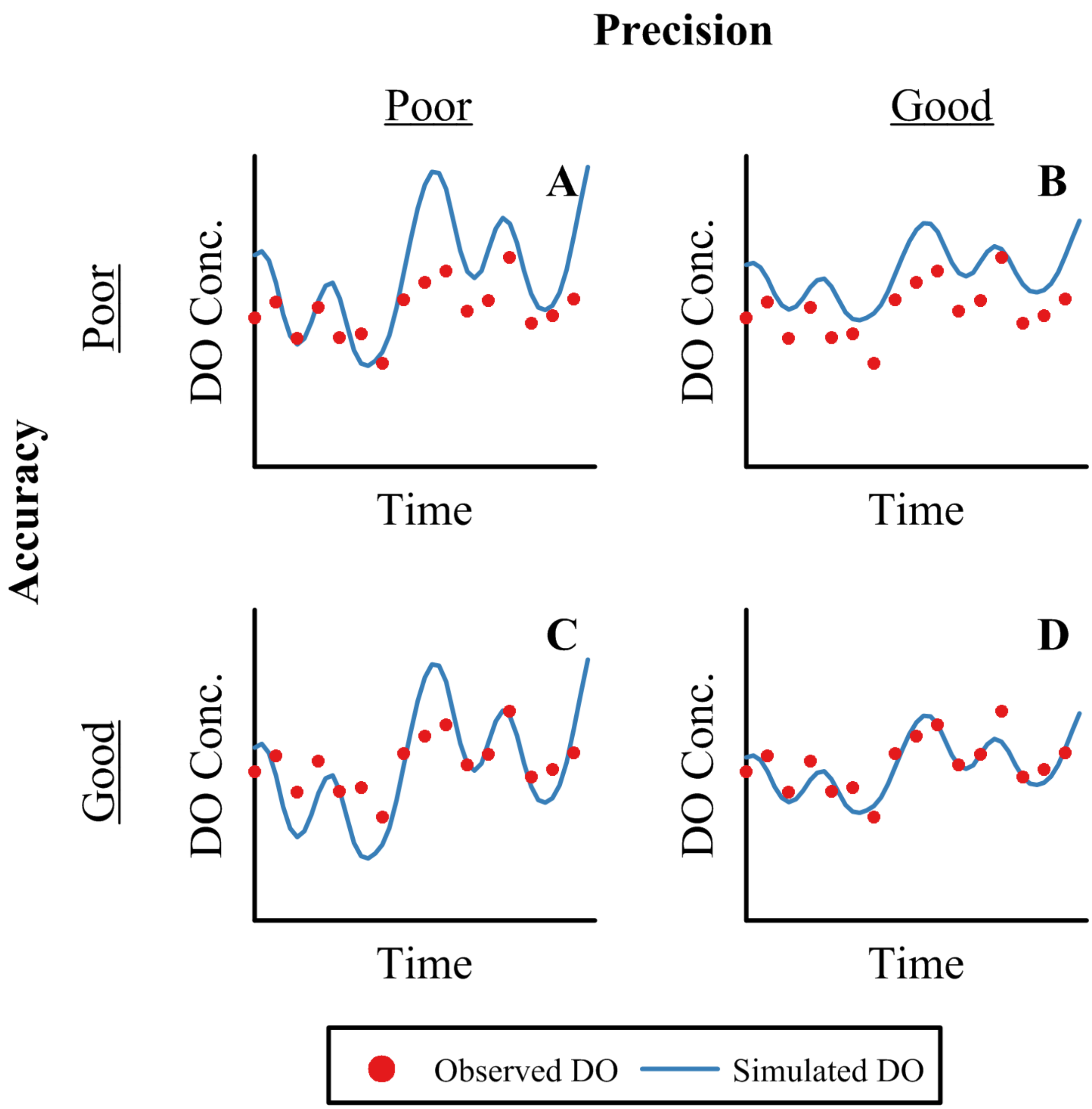


Figure 5. Time series plot of the San Joaquin River at Rough & Ready Island (RRI) observed dissolved oxygen (DO) concentrations and the May_2013 and November_2012 model baseline scenario dissolved oxygen (DO) concentrations.

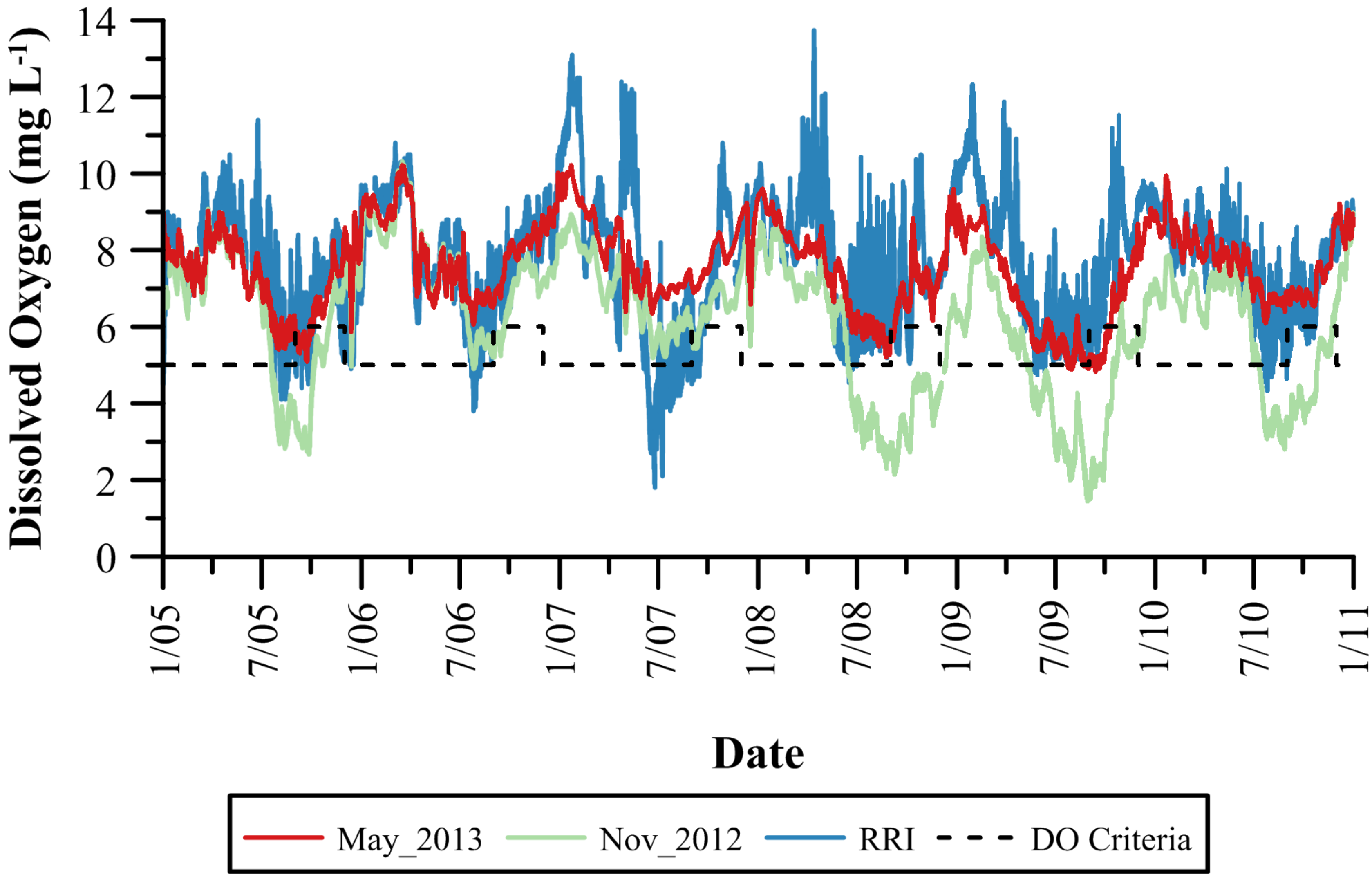


Figure 6. Relative error in predicting dissolved oxygen (DO) concentrations by year calculated using the May_2013 and November_2012 model baseline scenarios. The red line represents the mean relative error in the baseline scenario relative to the San Joaquin River at Rough & Ready Island (RRI) observed DO concentrations. The blue line represents the relative error in the model baseline scenarios for each year.

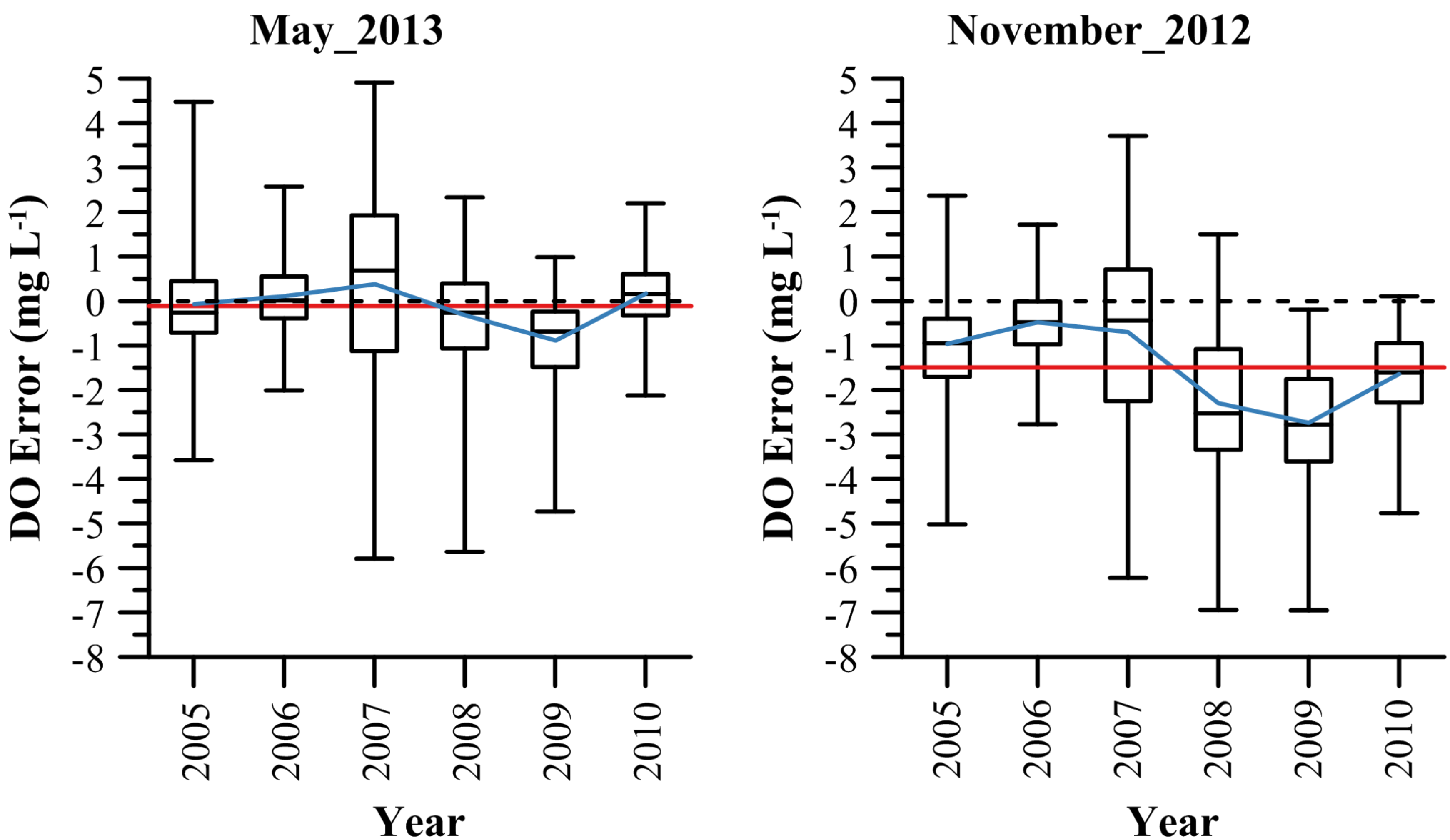


Figure 7. Relative error in predicting dissolved oxygen (DO) concentrations by month calculated using the May_2013 and November_2012 model baseline scenarios. The red line represents the mean relative error in the baseline scenario relative to the San Joaquin River at Rough & Ready Island (RRI) observed DO concentrations. The blue line represents the relative error in the model baseline scenarios for each month.

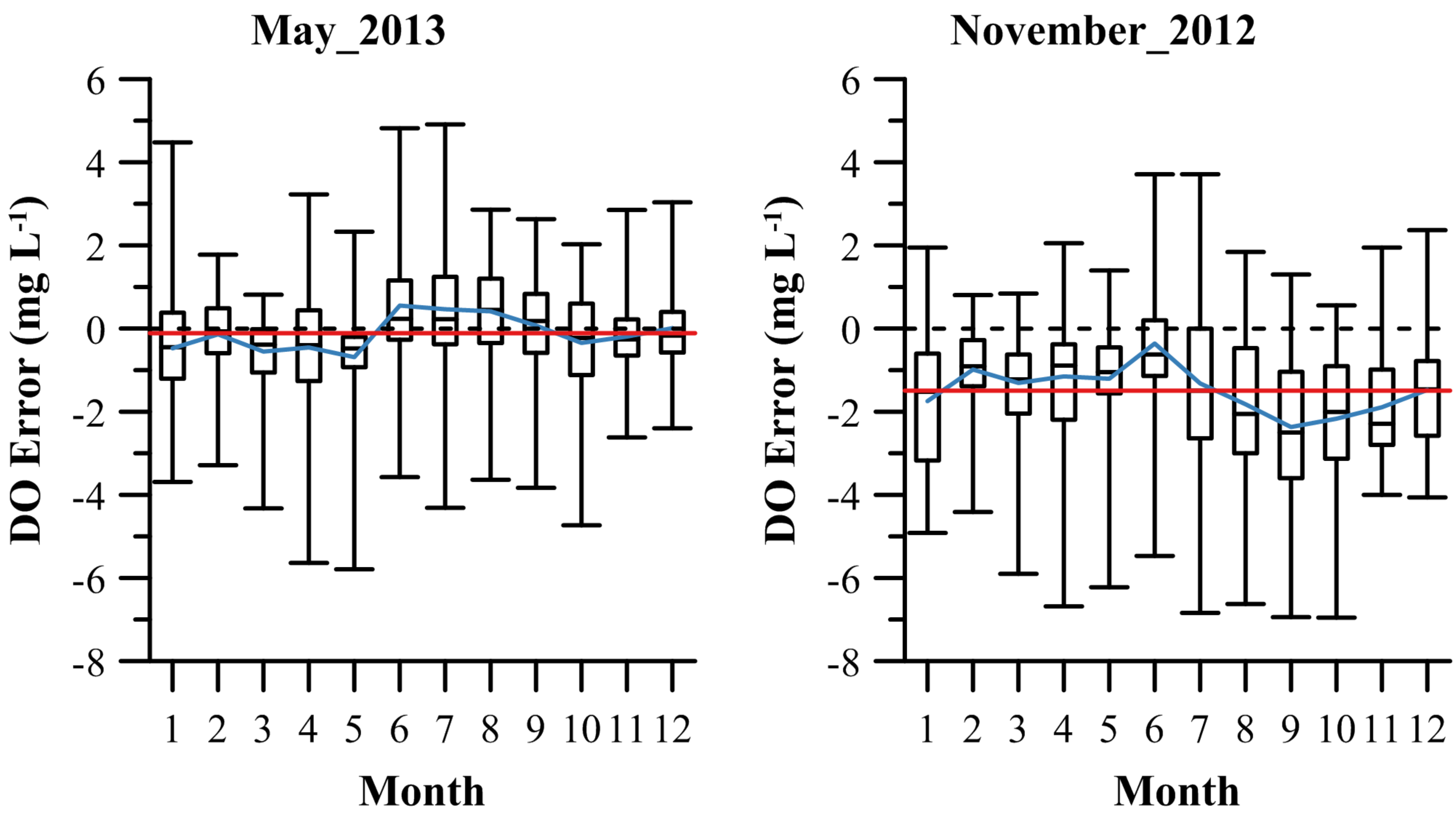


Figure 8. Absolute error in predicting dissolved oxygen (DO) concentrations by year calculated using the May_2013 and November_2012 model baseline scenarios. The red line represents the mean absolute error in the baseline scenario relative to the San Joaquin River at Rough & Ready Island (RRI) observed DO concentrations. The blue line represents the absolute error in the model baseline scenario for each year.

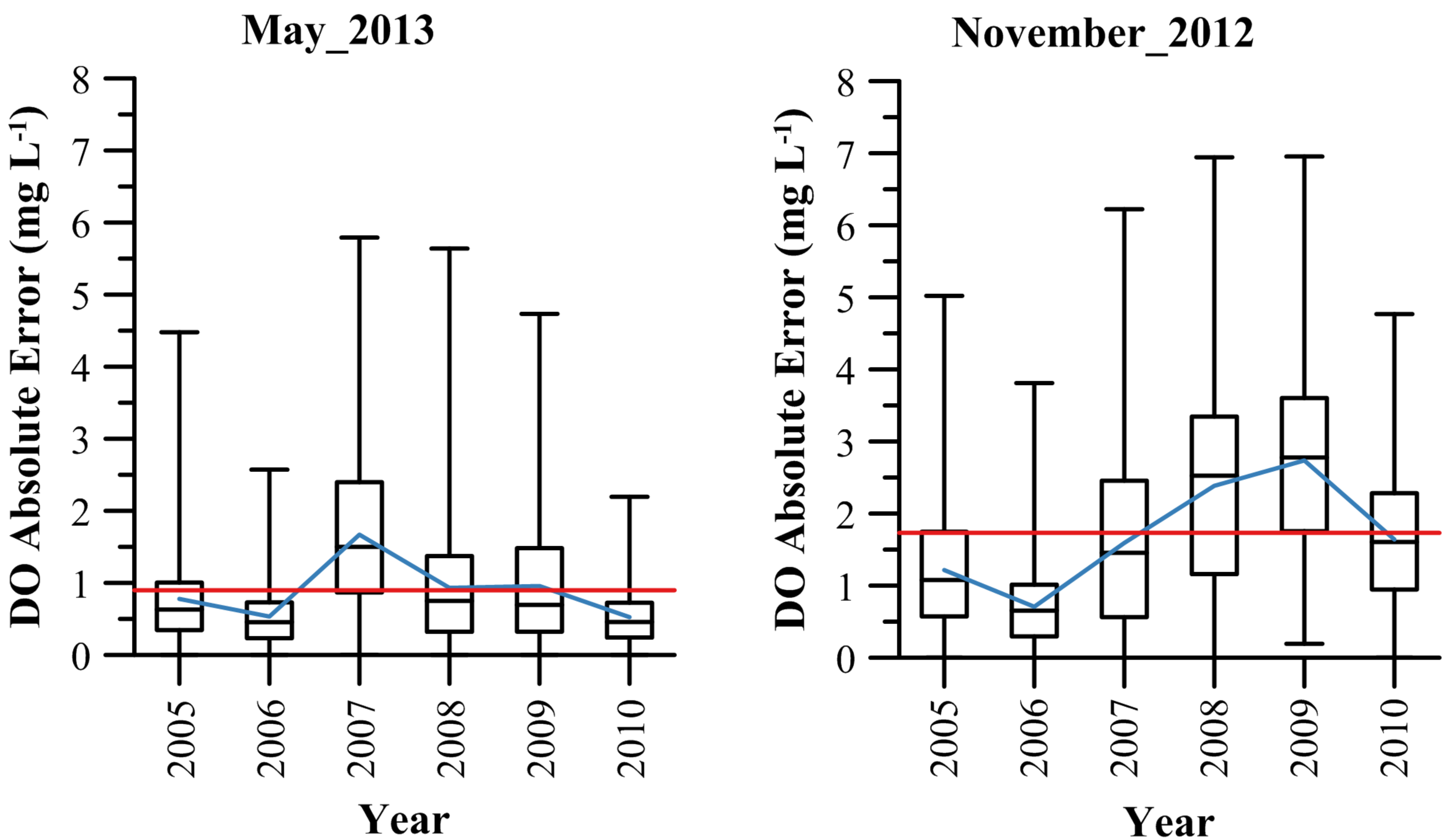


Figure 9. Absolute error in predicting dissolved oxygen (DO) concentration by month calculated using the May_2013 and November_2012 model baseline scenarios. The red line represents the mean absolute error in the baseline scenario relative to the San Joaquin River at Rough & Ready Island (RRI) observed DO concentrations. The blue line represents the absolute error in the model baseline scenarios for each month.

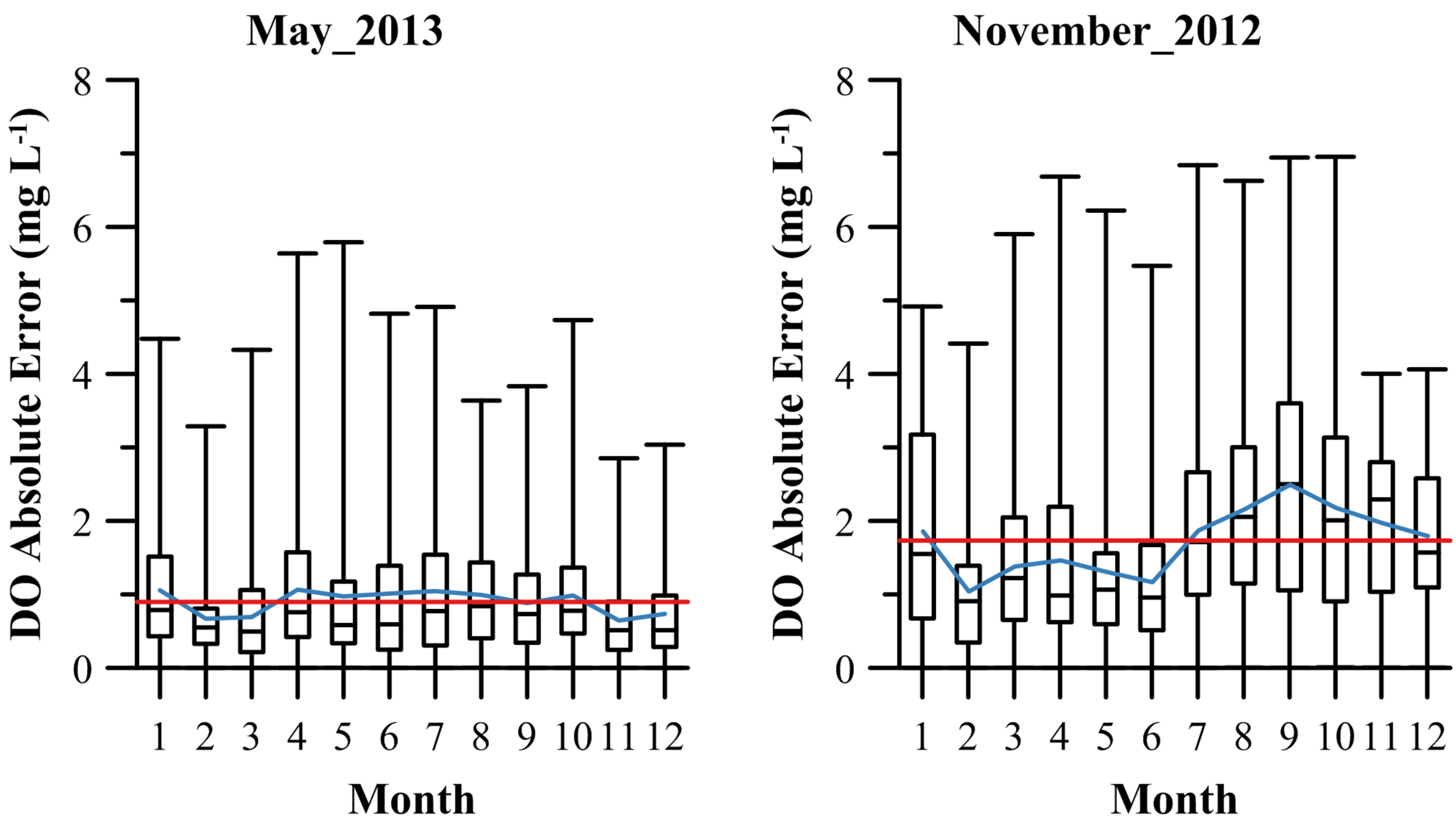


Figure 10. Percent of days where excursions occurred or were predicted for each month using the May_2013 model baseline scenario and the San Joaquin River at Rough & Ready Island (RRI) observed dissolved oxygen (DO) concentration data.

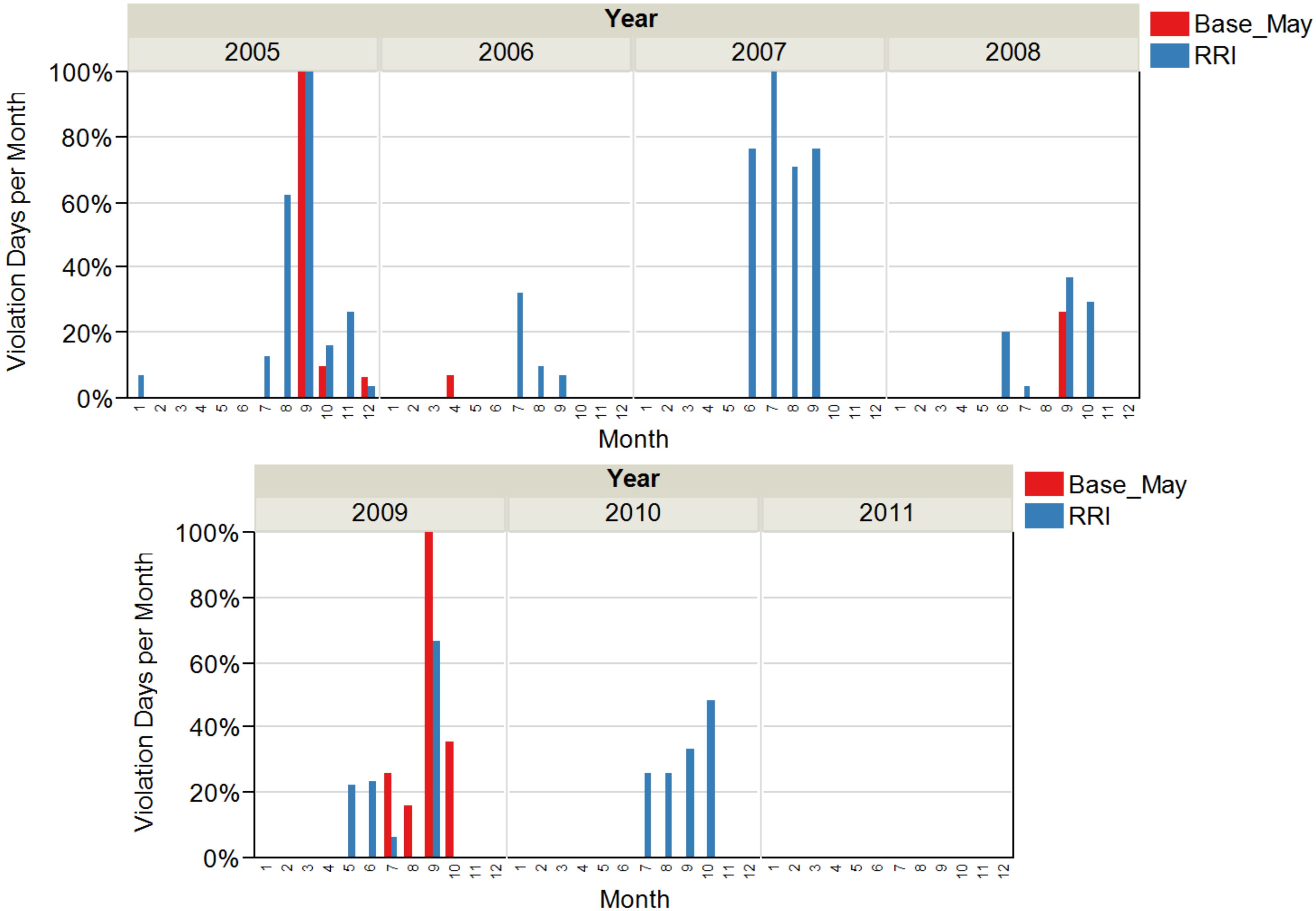
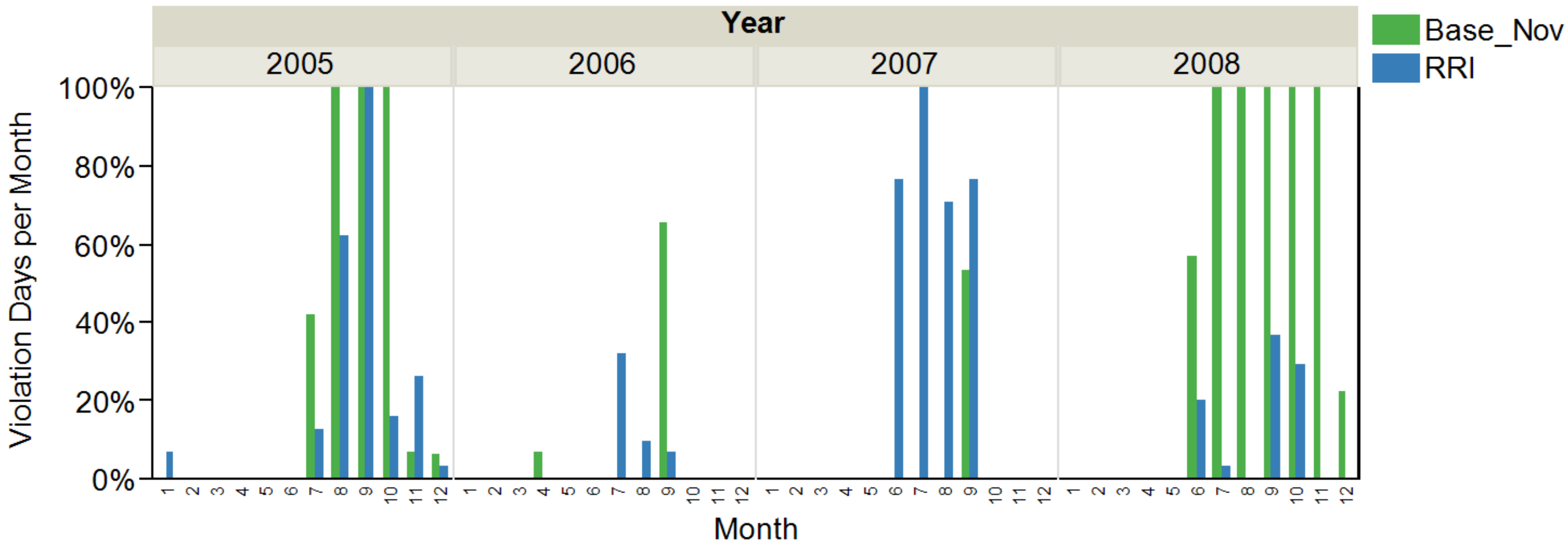


Figure 11. Percent of days where excursions occurred or were predicted for each month using the November_2012 model baseline scenario and the San Joaquin River at Rough & Ready Island (RRI) observed dissolved oxygen (DO) concentration data.



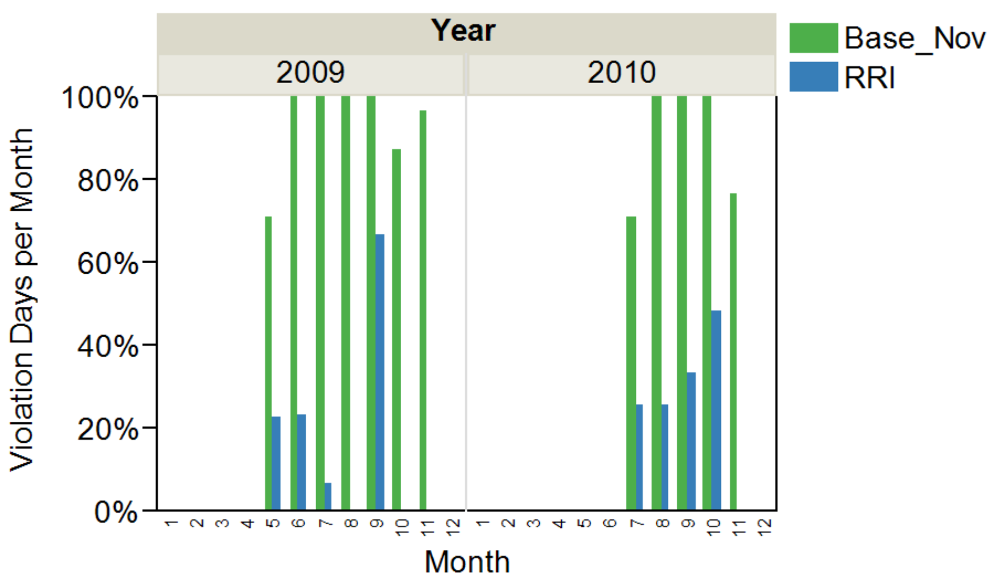
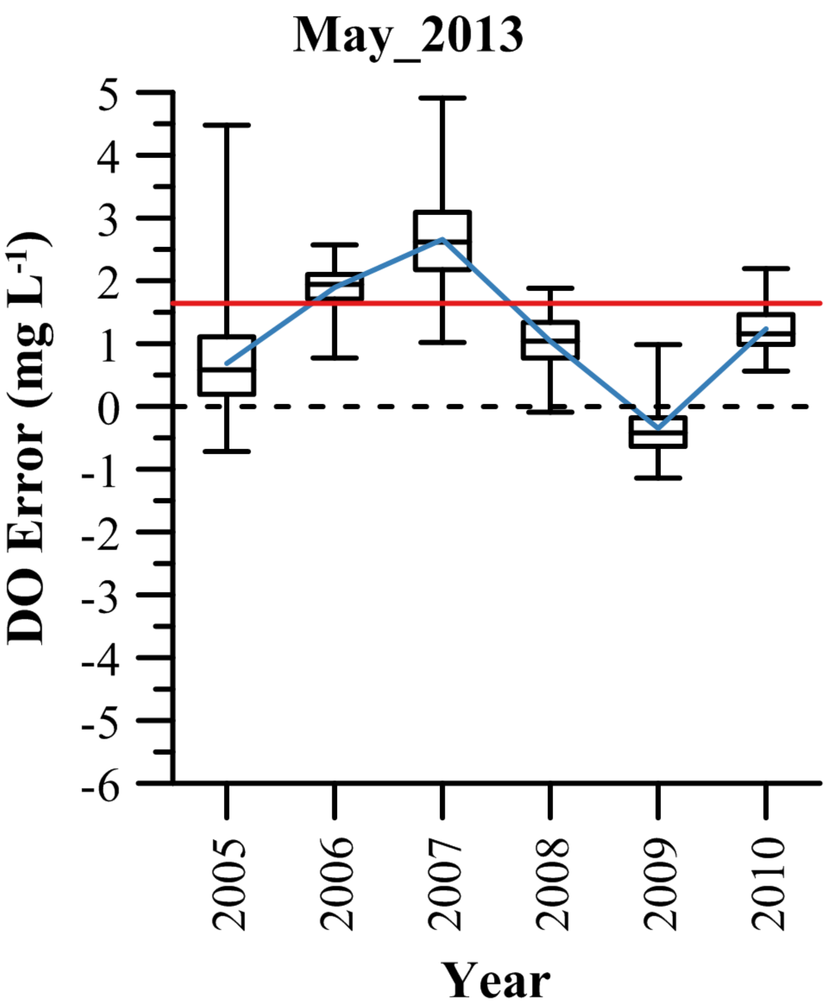


Figure 12. Relative error in predicting dissolved oxygen (DO) concentration by year calculated using the May_2013 and November_2012 model baseline scenarios when any hourly Rough & Ready Island (RRI) observed dissolved oxygen (DO) concentration was below the regulatory standards. The red line represents the mean relative error in the baseline scenario relative to the San Joaquin River at Rough & Ready Island (RRI) observed DO concentrations. The blue line represents the relative error in the model baseline scenarios for each year.



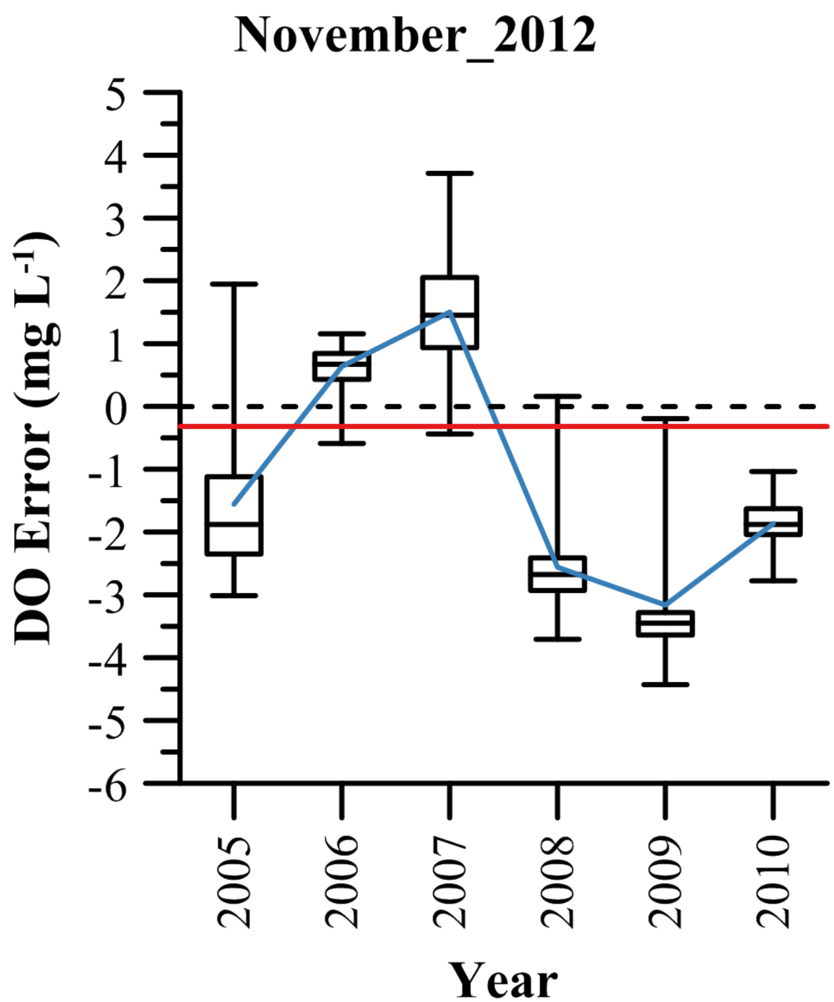
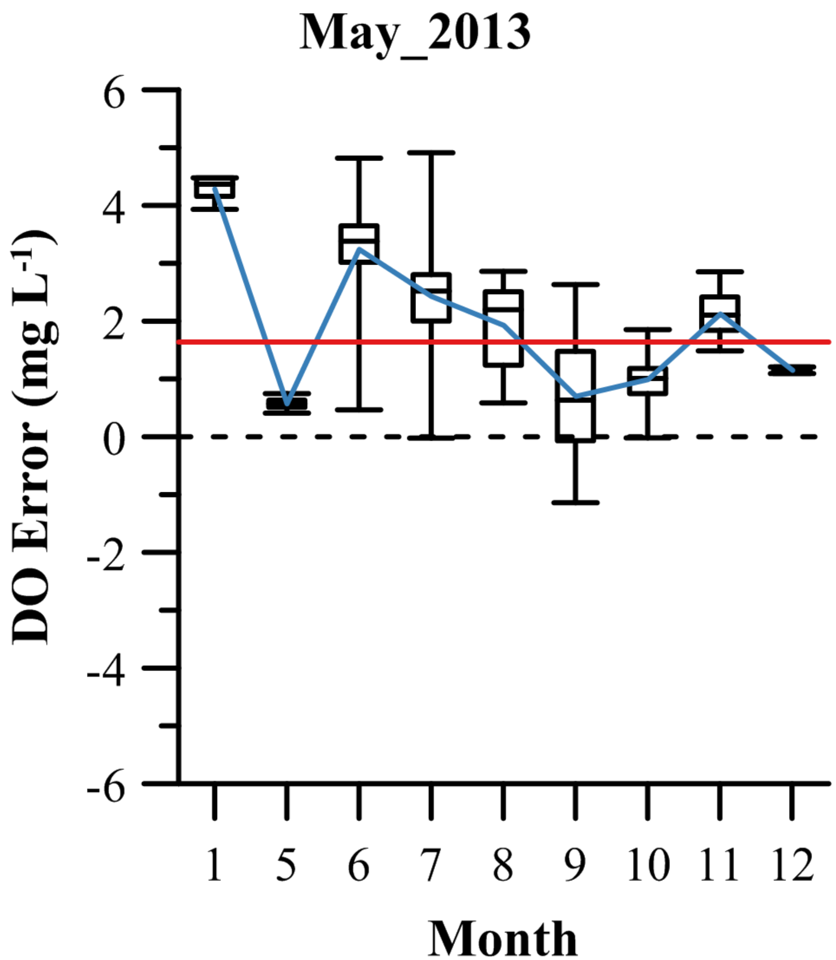


Figure 13. Relative error of the May 2013 and November 2012 Link-Node Base scenario by month during days where any hourly Rough & Ready Island observed dissolved oxygen (DO) concentration is below the regulatory standard. The red line represents the average mean error in the baseline scenario relative to the San Joaquin River at Rough & Ready Island (RRI) observed dissolved oxygen (DO) concentrations. The blue line represents the relative error in the model baseline scenarios for each month.



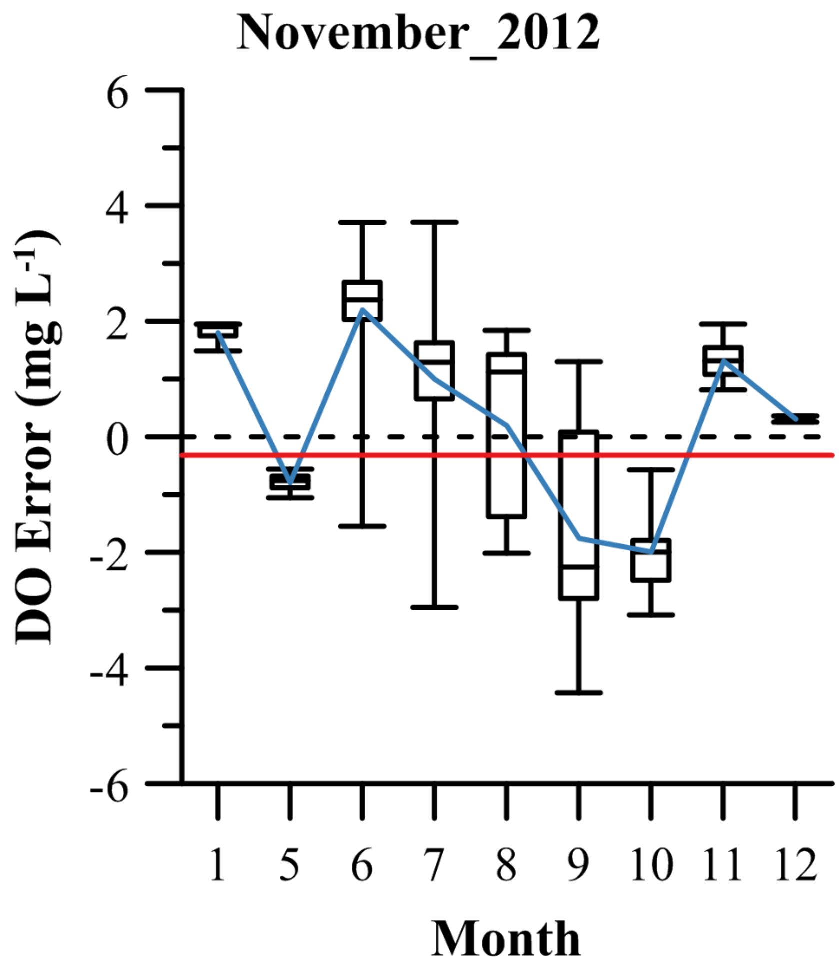


Figure 14. Mean percent of days with excursions by month for the San Joaquin River at Rough & Ready Island (RRI) observed dissolved oxygen (DO) concentrations and both the May_2013 and November_2012 model baseline scenarios, classified by water year type.

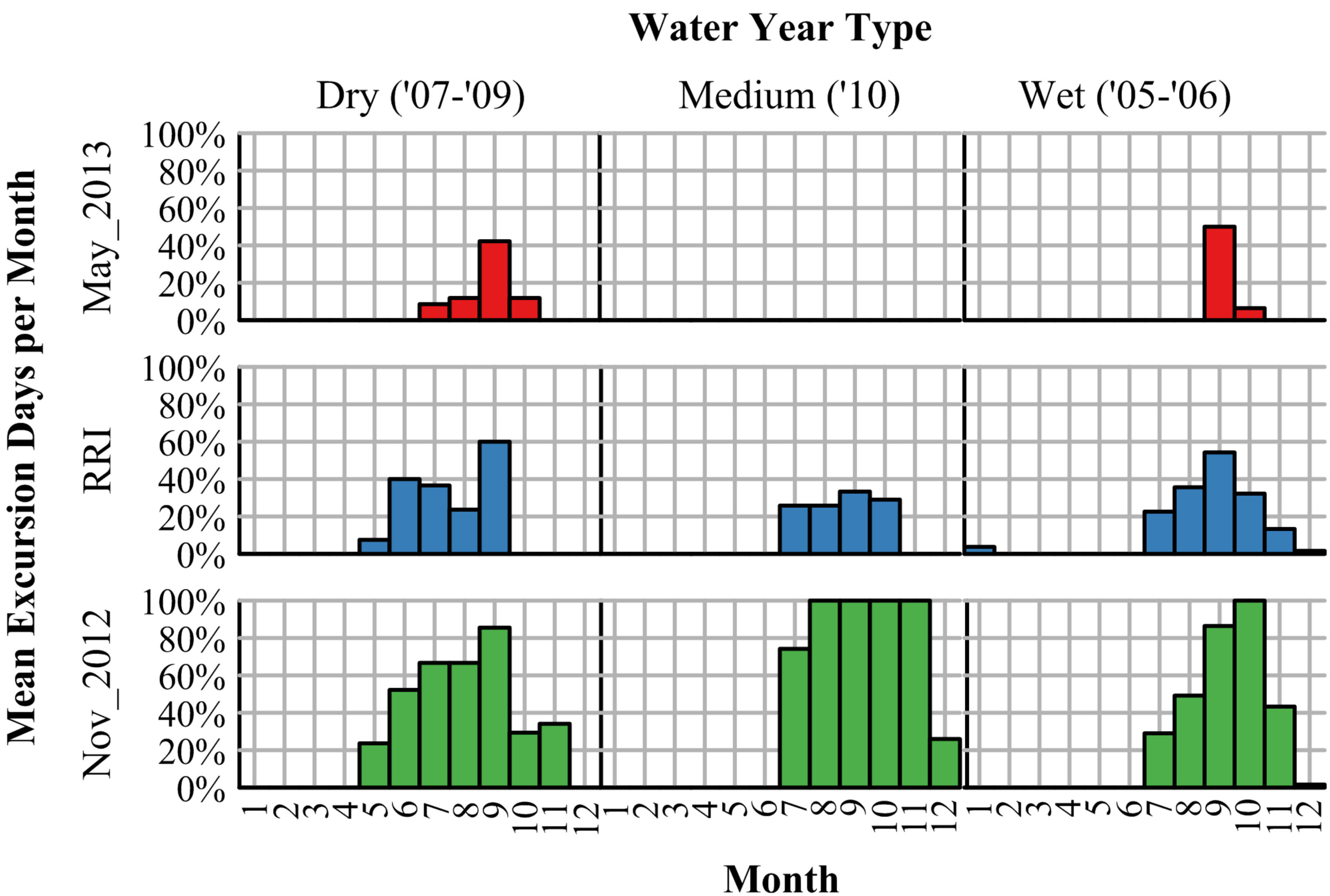


Figure 15. Predicted dissolved oxygen (DO) improvement based on results from the Link-Node model scenarios generated using the May_2013 model baseline scenario.

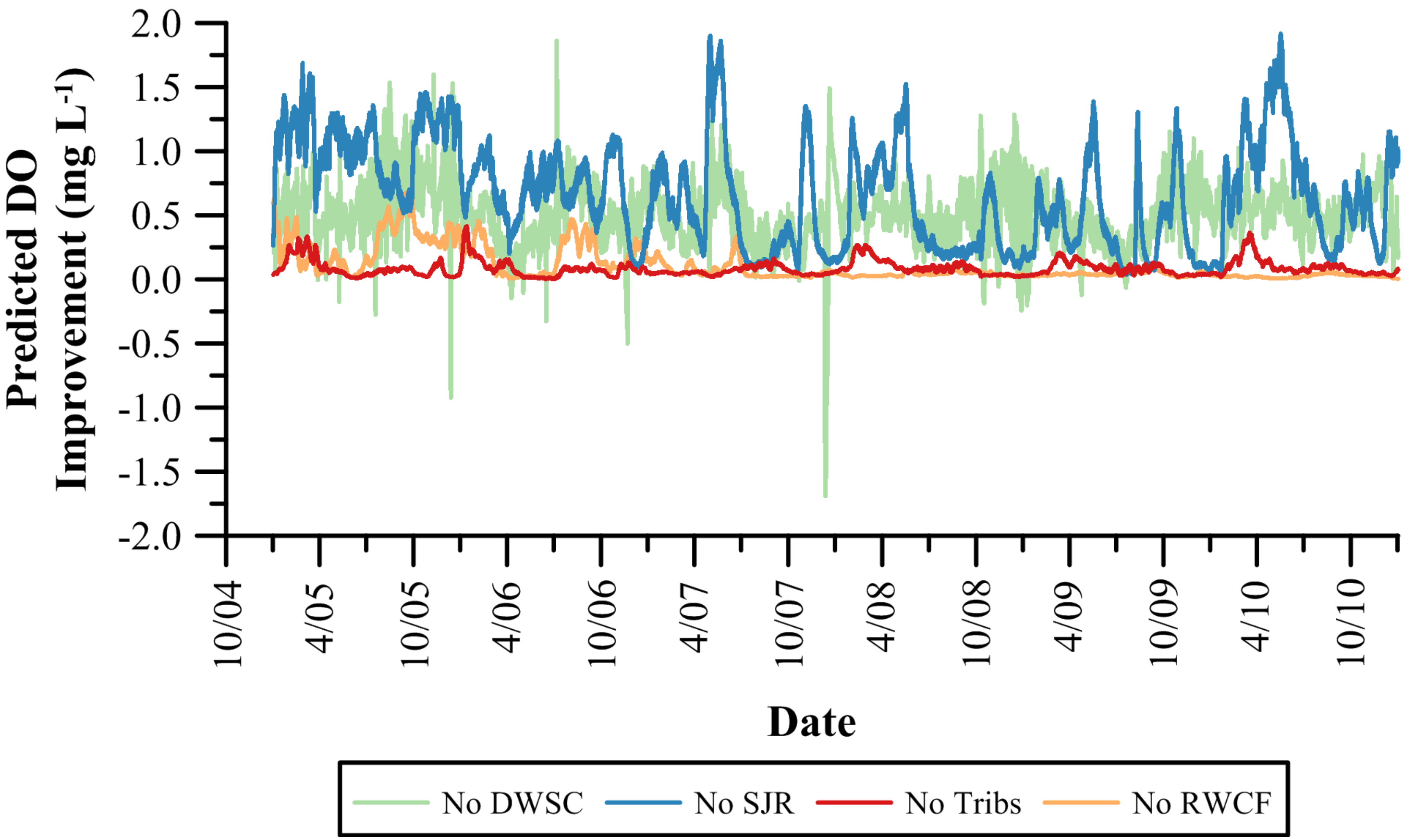


Figure 16. Predicted dissolved oxygen (DO) improvement based on results from the Link-Node model scenarios generated using the November_2012 model baseline scenario.

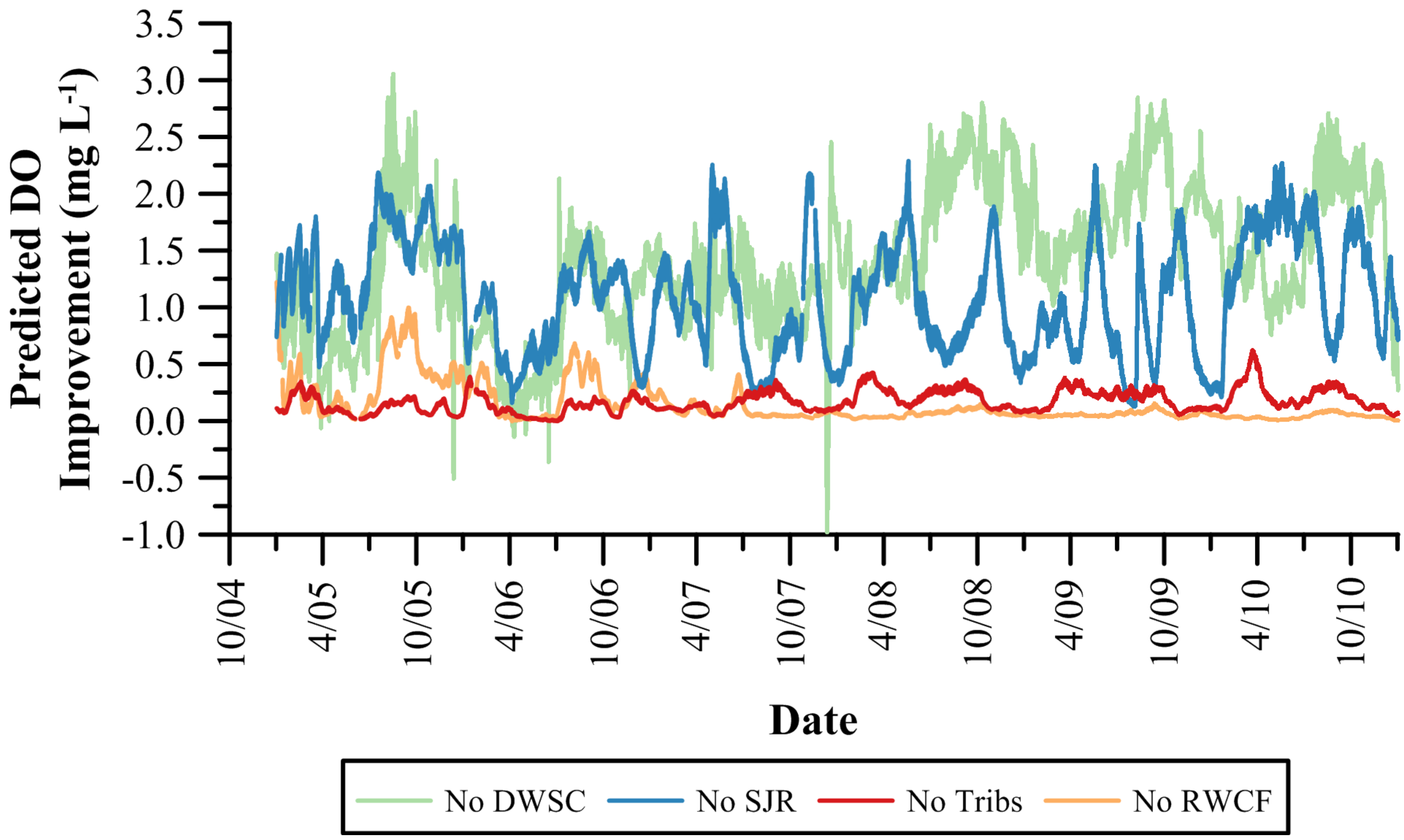
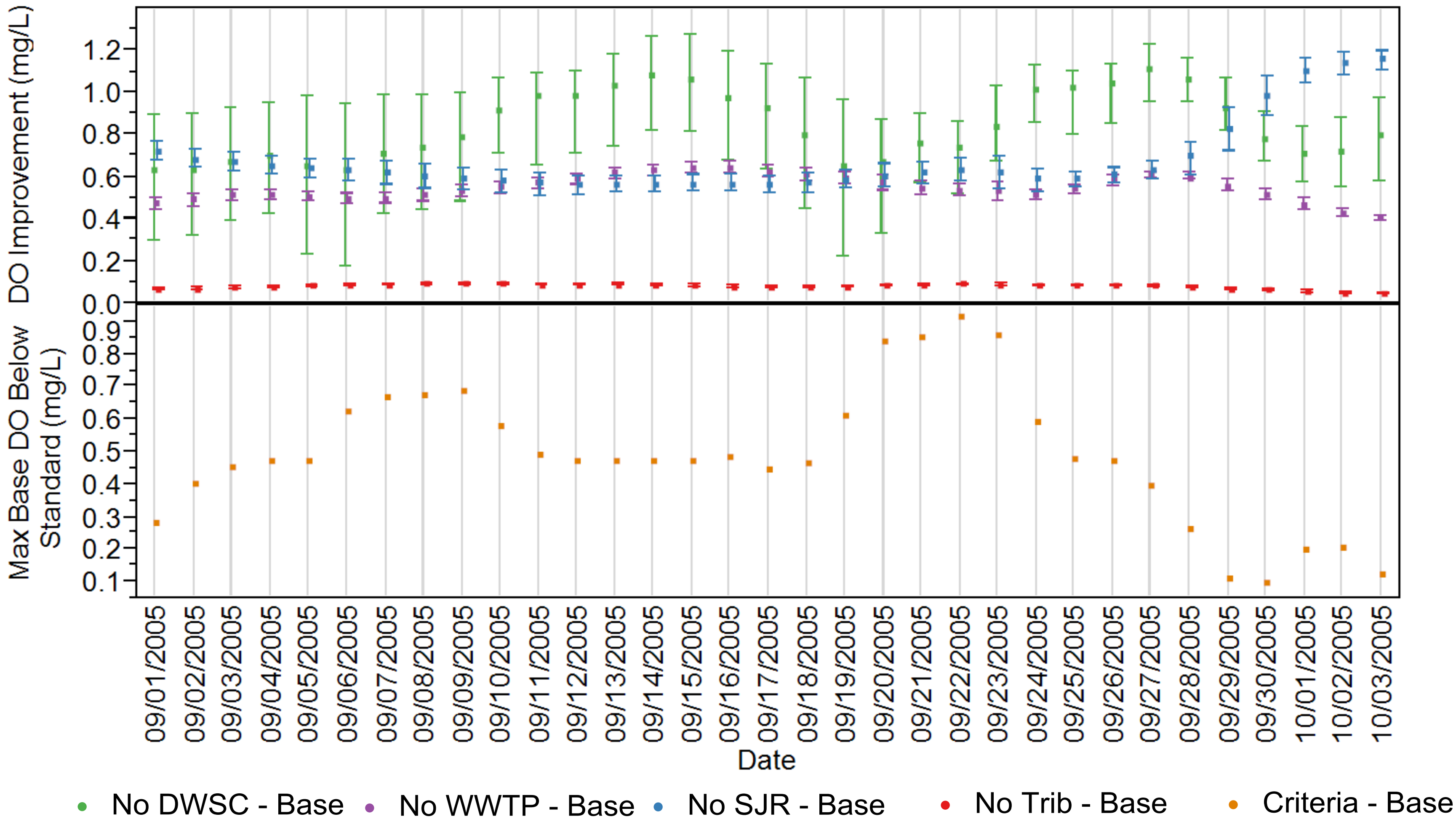


Figure 17. Predicted improvement in dissolved oxygen (DO) for days when excursions were expected to occur based on results from the Link-Node model scenarios generated using the May_2013 model baseline scenario. Each error bar indicates the minimum, mean, and maximum improvement for each day. The maximum daily difference between the dissolved oxygen (DO) standard and the results from the May_2013 model baseline scenario is shown for comparison. The 4/25/2006 model output was omitted due to an anomaly in range of improvement values. The x-axis, indicating dates, is not to scale.



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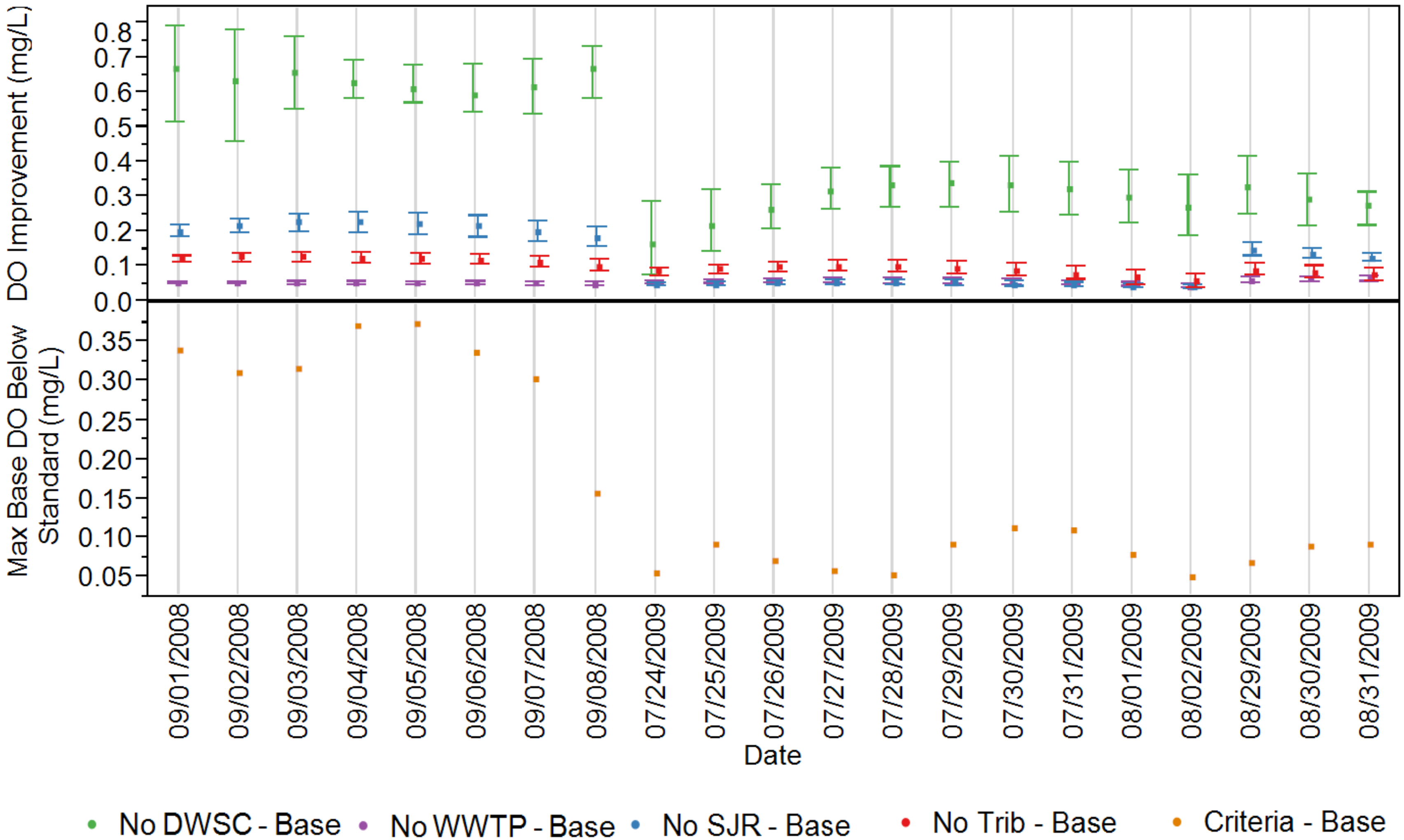

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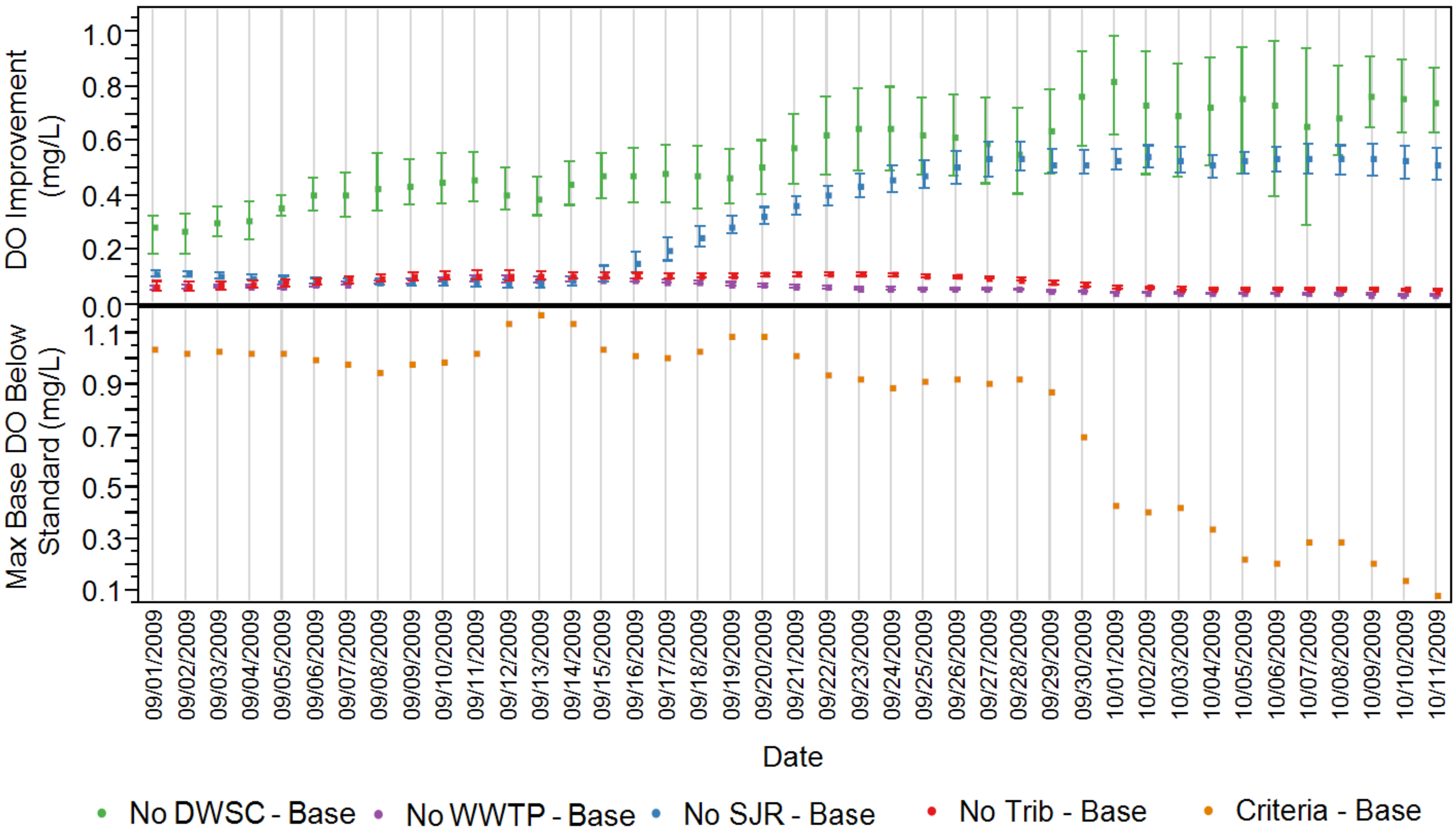

Figure 18. Predicted improvement in dissolved oxygen (DO) for days when excursions were expected to occur the top 5% of daily maximum DO excursions resulting from Link-Node scenarios calculated using the November_2012 model baseline scenario. Each error bar indicates the minimum, mean, and maximum improvement for each day. The maximum daily difference in the dissolved oxygen (DO) standard and the base scenario is shown for comparison. The 4/25/2006 model output was omitted due to an anomaly in range of improvement values. The x-axis, indicating dates, is not to scale.

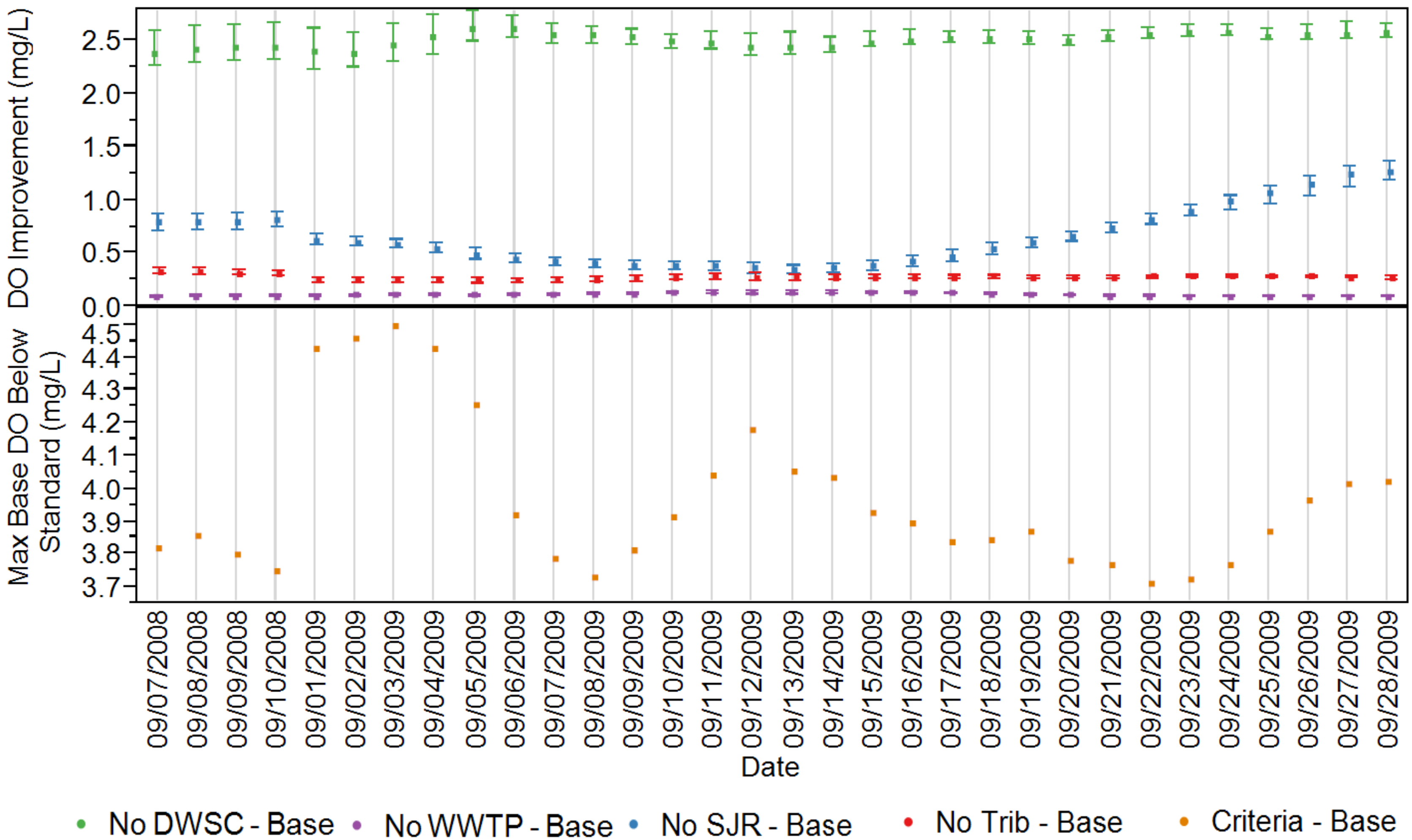

Figure 19. Excess net oxygen demand (ENOD) calculated using Link-Node model scenarios based on the May_2013 model baseline scenario where baseline scenario dissolved oxygen (DO) excursions were predicted. Positive values represent the DO mass load needed to meet the DO standard, while negative values represent the DO mass load that can be assimilated without violating the DO standard. The dashed lines delineate the start and end of a year. Smaller (more negative) values are considered more responsible for excursions than larger (more positive) values.

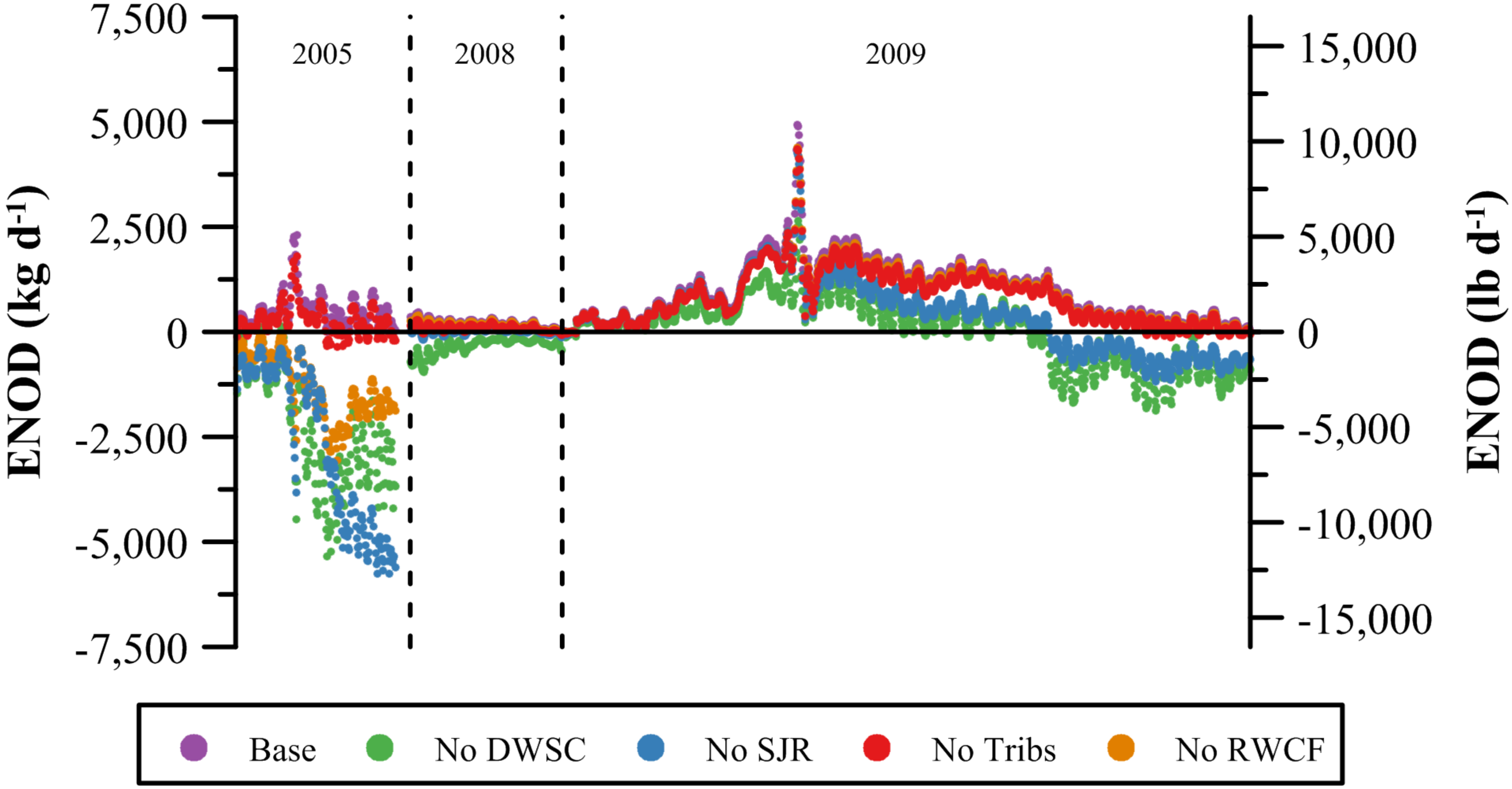

Figure 20. Excess net oxygen demand (ENOD) calculated using the Link-Node model scenarios based on the November_2012 model baseline scenario where baseline scenario dissolved oxygen (DO) excursions were predicted. Positive values represent the DO mass load needed to meet the DO standard, while negative values represent the DO mass load that can be assimilated without violating the DO standard. The dashed lines delineate the start and end of a year. Smaller (more negative) values are considered more responsible for excursions than larger (more positive) values.

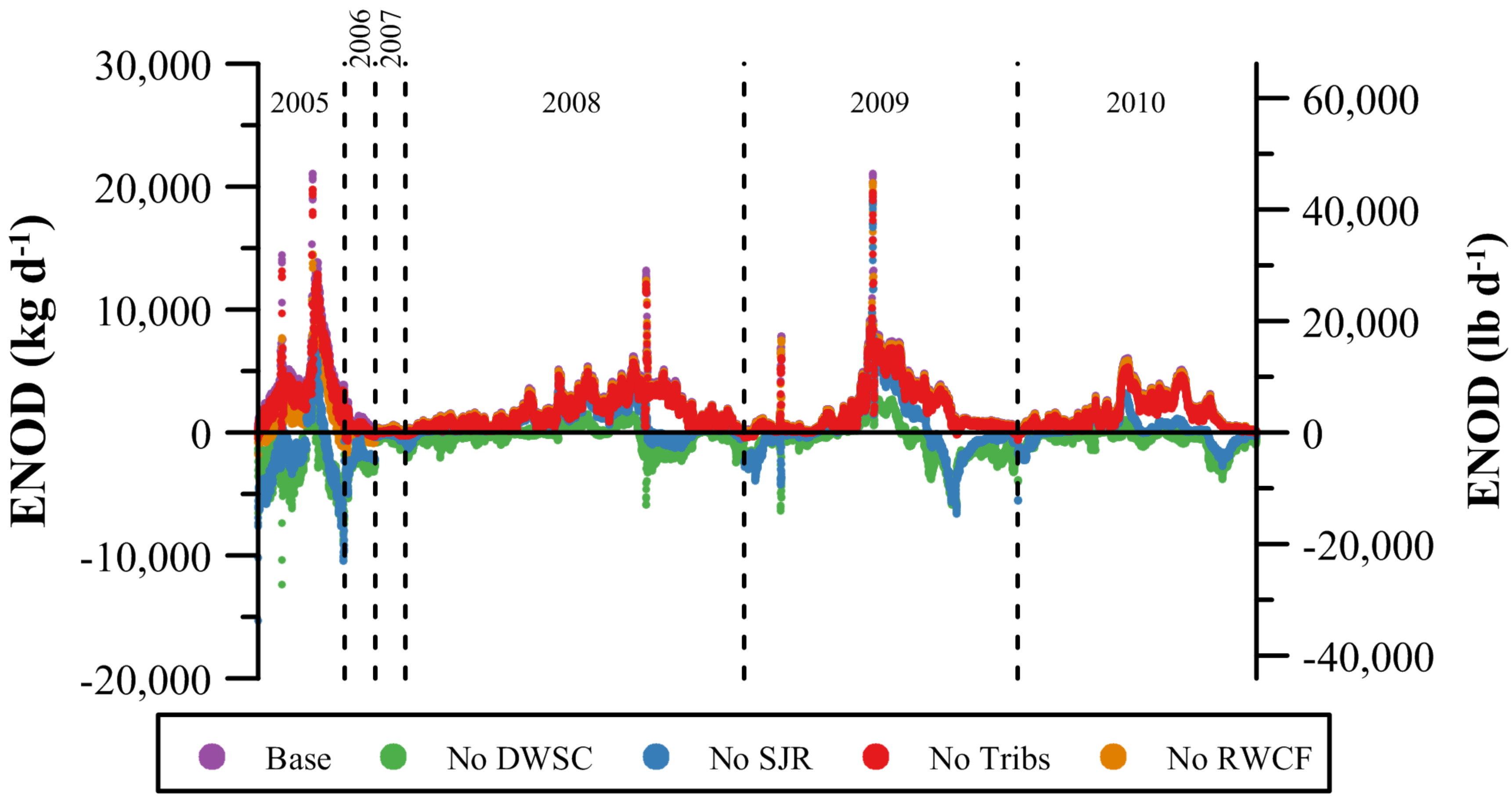

Figure 21. Relationship between daily minimum dissolved oxygen (DO) concentration and daily net flow for the Stockton Deepwater Ship Channel (DWSC) for the time periods: November 1995 to September 2000 (Gowdy and Grober, 2005) (left) and January 2005 to August 2011 (right). DO excursions did not occur below 3,000 cfs in the 1995-2000 time period and only one excursion occurred when net flow was below 3,000 cfs in the 2005-2011 time period.

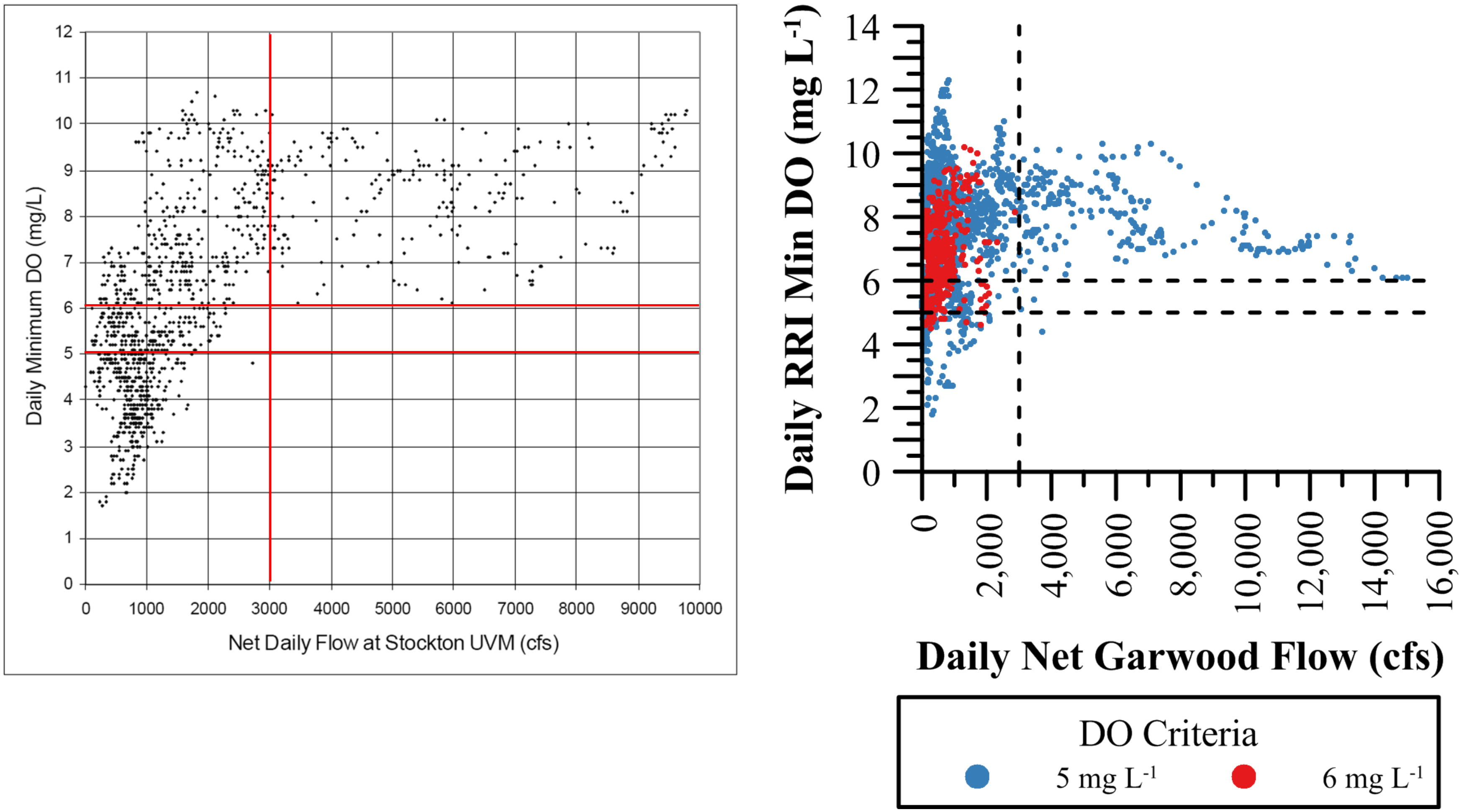

Figure 22. Dissolved oxygen (DO) improvement as predicted by the model, between the baseline and Flow+500 cfs scenarios for the May_2013 Link-Node model calibration.

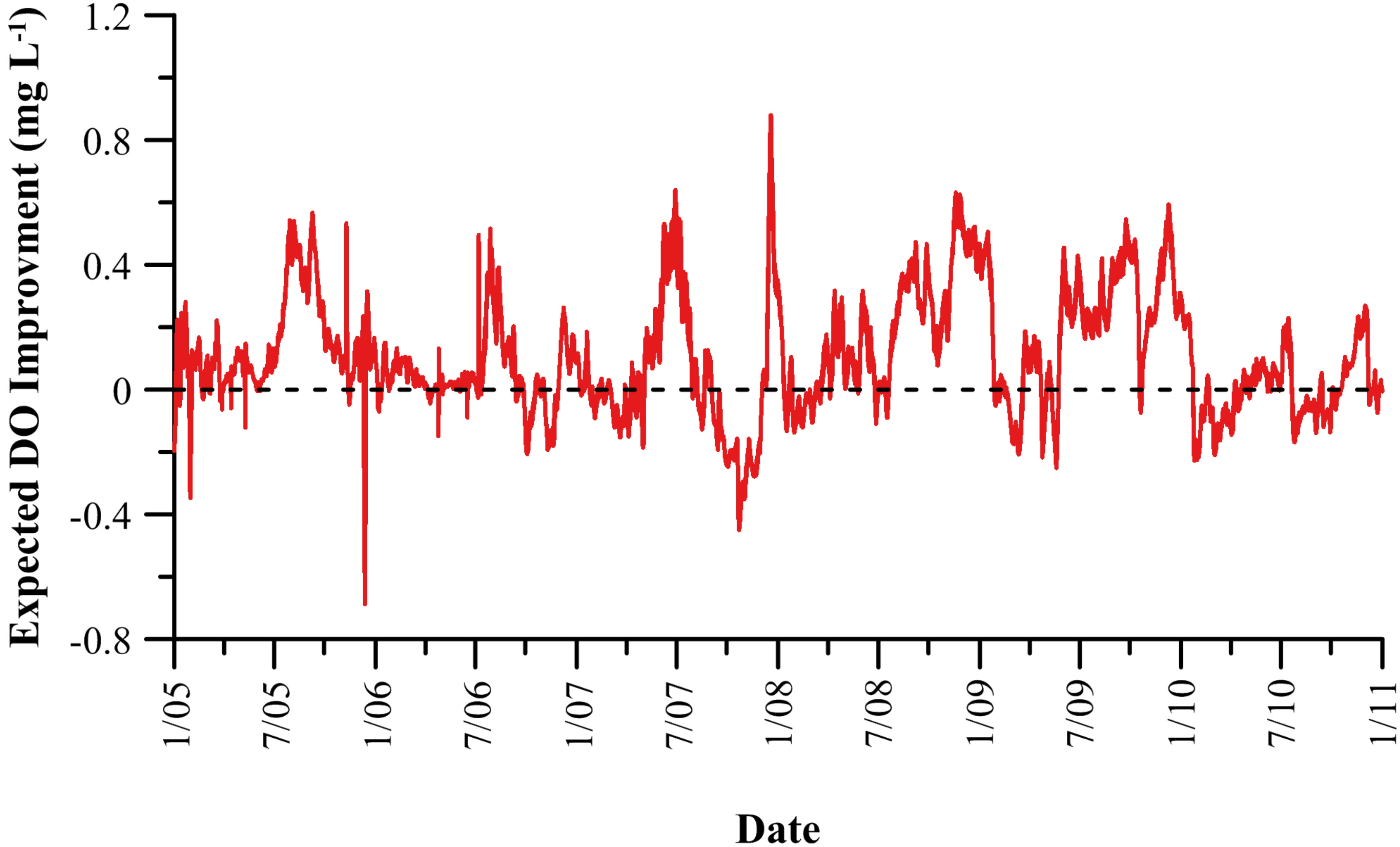

Figure 23. Mean percentage of days per month with dissolved oxygen (DO) excursions, as predicted by the model, in the baseline and Flow+500 cfs scenarios in the May_2013 Link-Node model calibration.

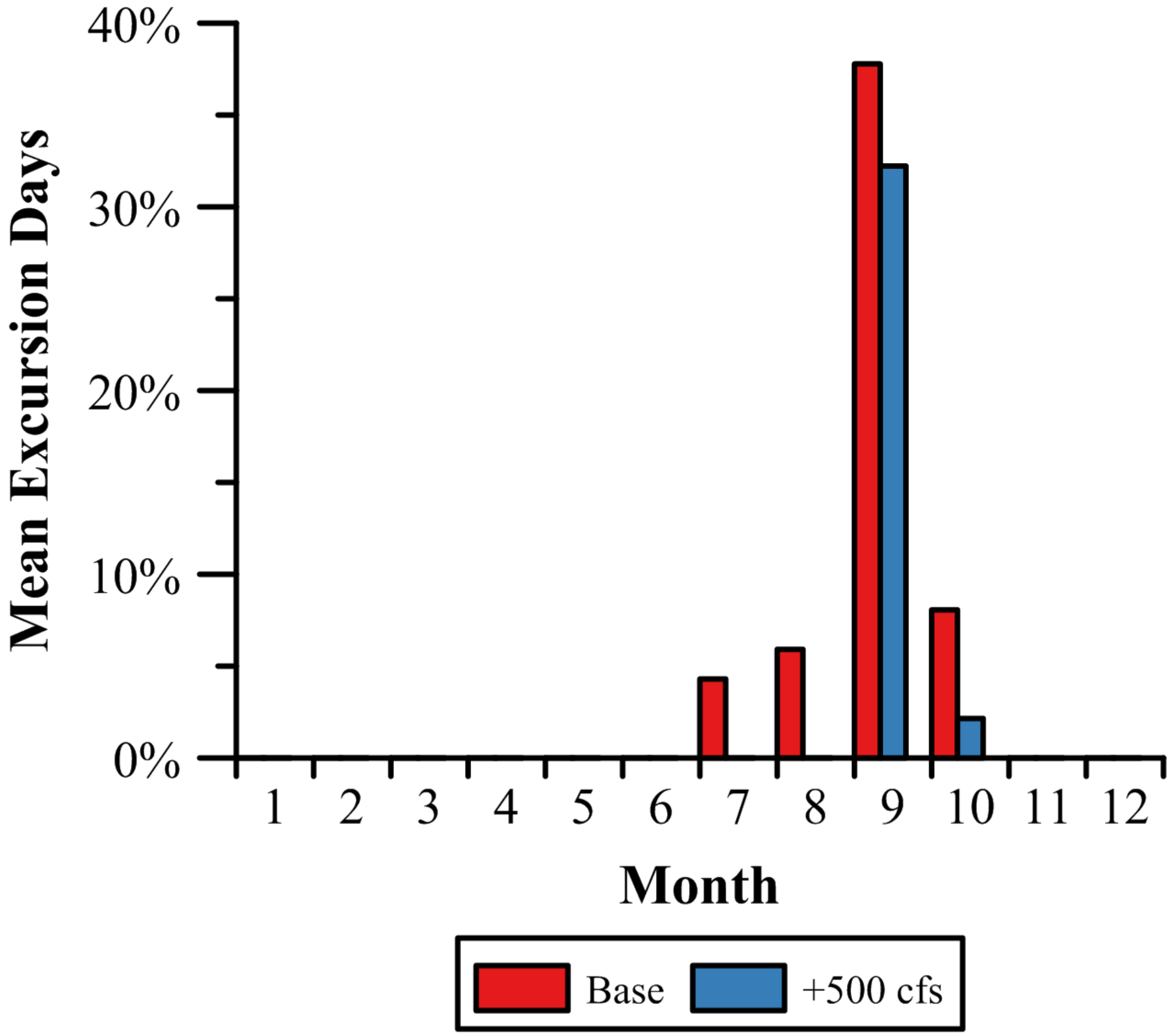

Figure 24. Excess Net Oxygen Demand (ENOD), as predicted by the model, for the baseline and Flow+500 cfs scenarios in May_2013 Link-Node model calibration.

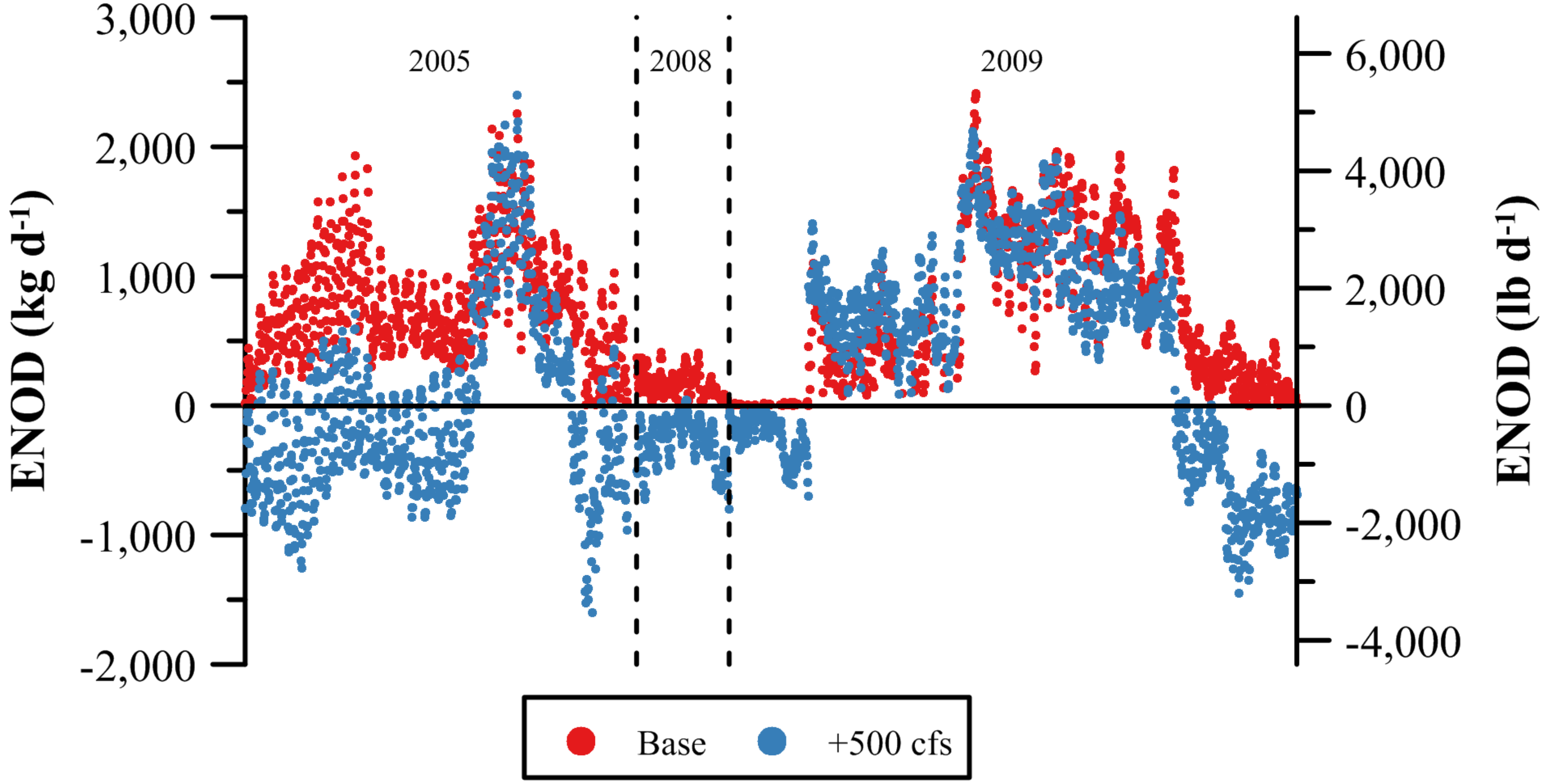

Figure 25. Excess Net Oxygen Demand (ENOD) calculated using the May_2013 Link-Node model calibration baseline dissolved oxygen (DO) predictions and observed net flow where ENOD is shown as a function of the DO model predictions.